# SENSORY COMMUNICATION

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# SENSORY COMMUNICATION

CONTRIBUTIONS TO THE SYMPOSIUM ON PRINCIPLES OF SENSORY COMMUNICATION

*July 19–August 1, 1959, Endicott House, M.I.T.*

WALTER A. ROSENBLITH, *Editor*



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# Preface

The postwar period has seen a surfeit of interdisciplinary symposia These symposia were a manifestation of several not unrelated facts the scientific universe was expanding at a rate that was hard to grasp or assess and the frontiers between the sciences seemed to be moving almost as much as science itself Communication between disciplines bad become more and more sketchy, and even within a given discipline communication had often become problematical At the same time many of the traditional fields among the life and behavioral sciences found themselves profoundly affected by the technological advances that had their origin in the physical sciences Experts in these technologies acquired a taste for the challenges of these less structured fields, but they sometimes lacked perspective and respect for the toughness of the problems that they proposed to tackle

It was with these difficulties that the numerous symposia attempted to grapple Like other scientific meetings these interdisciplinary symposia were unequal in quality At the outset the freshness of the confrontation, the unorthodox approaches, promised a great deal. But as time wore on it became clear that while the symposia were productive of suggestive ideas they were no substitute for the workaday interaction of experimentation and theory making Responsible workers in the behavioral and life sciences became increasingly squeamish about the one-day symposium in which mathematicians, physicists and engineers vented frequently the belief that the intelligent application of some rather elementary notions from mathematics and physics should yield spectacular results in the solution of a variety of thorny problems The brain, perception, learning thinking, that is to say, all topics that in Warren Weaver's phrase are characterized by "organized complexity," were the explicit target of these optimistic predictions

The biological scientists who had beeo trained in the more traditional approaches adopted a retaliatory stance in which they were only too often satisfied to point to the truly appalling complexities of their experimental data The two parties separated, leaving behind numerous volumes that were represented to be high fidelity transcriptions of the tape recordings of these encounters Relatively few among the symposiasts got beyond the hors d oeuvres and stayed, as it were for dinner

And yet these intellectual skirmishes made their imprint upon the

kind of questions that laboratory and computer scientists began to ask and on the results they obtained Here were at least partial payments on the perhaps overgenerous promissory notes

Throughout the nineteenth century sensory problems had proved attractive to a variety of scientists who had also worked in the physical sciences—Young Ohm, Helmholtz, Fechner Mach to name just a few The twentieth century perpetuated and modified this tradition Electronic and communications engineers concerned with the telephone and with radio television and photography discovered their stake in the understanding of man's sensory performance The engineers were largely responsible for pointing out how fruitful the application of theoretical concepts à la Wiener Shannon might be in an analysis of human information handling The advent of large computers and of complex weapons systems put a premium on our ability to couple man to these machines that seem so capable of simulating and amplifying many aspects of man's intelligent behavior

Thus there arose albeit in a changed context, a renewed concern with perception Attempts to program computers to recognize certain patterns to translate from one language into another, and more generally to solve certain classes of logical problems led to an emphasis upon man's cognitive functions, to a reconsideration of the role that sensory processes play in this type of symbolic behavior But the formulation that was couched in terms of the processing of sensory information enabled the scientists of the post World War II period to transcend (perhaps only to bypass or even sidestep) the traditional dichotomy between sensation and perception

It thus appeared worth while to bring together a group of scientists and engineers who had themselves done research on problems of sensory communication and who were willing to listen to neurophysiologists expound up-to-date neurophysiology, or psychophysicists talk about contemporary psychophysics instead of being satisfied with their own version of the other man's science

These considerations led late in 1957 to the not entirely original idea of a multidisciplinary international symposium on principles of sensory communication Before too long the Office of Scientific Research of the U S Air Force expressed interest in sponsoring such a meeting provided that the collaboration of a representative group of scientists could be assured. In the fall of 1958 an international organizing committee was formed consisting of F Bremer, T H Bullock, A Fessard R Galambos, W D Neff C Pfaffmann S S Stevens and W A Rosenblith

Thanks to the active support of this committee we were able to assemble a group whose broad ranging competence in the area of sensory communication was unquestionable We regretted, however, that a variety of circumstances forced a few scientists to decline our invitation and left us with a somewhat less "balanced representation" than we had hoped for

If communication on sensory communication was to take place, the number of symposium participants had to be limited. The number of full fledged participants who could be accommodated was further limited by

our conviction that appropriate living and dining arrangements are requisite for the effective interchange of ideas We were grateful, therefore, to our guests (practically all of whom were from the Boston area) who were willing to attend single sessions only during the first week, and who nevertheless participated so fruitfully in the deliberations of the working groups during the second week We appreciated also the helpful participation of H O Wooster, L Butsch, H O Parrack, H Savely, and J Steele, who attended the meetings as representatives of the sponsor, the U S Air Force, whose generous, nondirective support it is a pleasure to acknowledge

The symposium was held during the last two weeks of July 1959 at M I T 's Endicott House in Dedham a Boston suburb Sunday night Profes sor Jerome B Wiesner, Director of the Research Laboratory of Electronics and Chairman of the Steering Committee of its Center for Communication Sciences, opened the proceedings by extending the Institute's official welcome Thereafter, the participants and guests at this inaugural session listened with evident pleasure to E G Boring Edgar Pierce Professor of Psychology Emeritus at Harvard University, who applied his wisdom, insight, and wit to a review of the history of afferent communication

After this auspicious send off, the more formal sessions started on Monday morning and continued throughout the first week, every morning and every evening after dinner The afternoons were left open for laboratory visits,* informal discussions, walks in the park, or dips in the Endicott House pool The chapters in this volume correspond by and large to the quasi formal presentations of the first week After a week end break most of the participants reassembled in several working and discussion groups There was no attempt to record these exchanges of ideas and data on tape, and we can only hope that the section on comments and the final versions of chapters in this volume reflect some of the many cogent points that were raised, often in an informal manner

Of the several pleasant social occasions that accompanied the symposium one deserves special mention a reception and tea at Brandegee House, tendered to the participants by the American Academy of Arts and Sciences Hudson Hoagland and Ralph Burhoe acted as hosts on behalf of the Academy Council and the Committee on Informal Gatherings Hoaglands warm words of welcome evoked a delightfully spirited response from W A H Rushton, F R S

Rushton said, "It was during the American Revolution that this Academy was founded, and I suppose the chief factors were the activity of great Boston characters and the disappearance of the King of England You never know what circumstances will found an Academy, and with our Royal Society (upon which you said your Academy was modeled) the conditions were just the other way For with the death of Oliver Cromwell the King

* It is a pleasure to thank E H Land, F A Webster D R Griffin K. D Roeder, J Y Lettvin H R Maturana, S W Kuffler D H Hubel and T N Wiesel who arranged these laboratory visits and demonstrations which were much appreciated by the symposium participants

of England reappeared and it was the Puritans who went—to Boston as I suppose

"The descendants of these Boston emigrees—John Adams and the rest—were the men who gave you your noble and liberal Charter, parts of which we should like to take as an ideal for the matter and manner of our meetings For in matter we too wish 'to promote and encourage medical discoveries, mathematical disquisitions, philosophical inquiries and experiments,' and in manner I hope that our meetings 'may tend to advance the interest, honour, dignity and happiness of free, independent and virtuous people'"

A given scientific gathering owes a large share of its success to a great number of people, many of whom are nonscientists Acknowledgment of this debt would gain in meaning were it accompanied by a functional flow diagram of auxiliary activities How otherwise can one do justice to the efforts of those who struggle with the ever present inadequacies of slide projectors, who act as chauffeurs and guides, who perform the multifarious duties that make intellectual discussions at an international scale possible? This meeting had its oversize and overtime share of such efforts No one showed more dedication in planning and operation than my assistant, Mrs Aurice Albert. Her devotion to the success of the symposium fully merited the high tribute the participants paid her in the final session

The atmosphere of the symposium owed much to the good management of Mrs Gertrude Winquist, who presides over Endicott House Most of the participants lived in these comfortable and congenial surroundings, and all of them socialized there repeatedly

The staff of the Research Laboratory of Electronics under the direction of R A Sayers, provided many services with customary efficiency and dispatch. My colleagues from the Laboratory's Communications Biophysics group unselfishly gave of their time in a variety of ways, for example, they provided several demonstrations of the processing of neuroelectric data by means of high-speed electronic computers My colleague, Dr Eda Berger Vidale, contributed in many ways to the production of this volume in particular, she spent untold hours in the compilation of the subject index

Finally, I should like to express my personal gratitude to Geraldine Stone She has been much more than an assistant to the editor of this volume or an intermediary between the authors and the editor Her knowledgeable, persistent, sensitive and indefatigable efforts are visible on almost every page of this book. Miss Stone collaborated with Miss Constance D Boyd of the M I T Press, who contributed her measure of serious and patient labors No editor could hope for more capable and dedicated associates

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# Contents

# SENSORY COMMUNICATION

1

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# The Psychophysics of Sensory Function

An inquiry into the nature of the sensory process begins properly with psychophysics, the hundred year old discipline concerned with the responses that organisms make to the energies of the environment We live in a restless world of energetic forces, some of which affect us and some of which, like radio waves, impinge upon us and pass unnoticed because we have no sense organs able to transduce them But we see lights, hear sounds, taste substances and smell vapors, and it is these elementary facts of psychophysics that stir our interest in the anatomy and physiology of the mechanisms that make sensation possible An orderly and systematic account of sensory communication must include a delineation of *what* is perceived as well as an explanation of *how* perception is accomplished In this sense, psychophysics defines the challenge it tells what the organism can do and it asks those who are inspired by such mysteries to try, with scalpel, electrode, and test tube, to advance our understanding of how such wonders are performed

It must be confessed at the outset that psychophysics has often failed to do its part of the job with distinction Its task is not easy For one thing long standing prejudices, derived in great measure from a chronic dualistic metaphysics, have triggered a variety of stubborn objections whenever it has been proposed that sensation may be amenable to orderly and quantitative investigation You cannot, the objectors complain, measure the inner, private, subjective strength of a sensation Perhaps not, in the sense the objectors have in mind, but in a different and very useful sense the strength of a sensation can, as we shall see, be fruitfully quantified. We must forgo arguments about the private life of the mind and ask sensible objective questions about the input-output relations of sensory transducers as these relations are disclosed in the behavior of experimental organisms, whether men or animals

Another difficulty is that psychophysics had an unfortunate childhood. Although Plateau in the 1850s made a half hearted attempt to suggest the proper form of the function relating apparent sensory intensity to stimulus intensity, he was shouted down by Fechner, who saddled the infant discipline with the erroneous "law" that bears his name (see Stevens, 1957*b*) Perhaps the hardest task before us is to clear the scientific bench top of the century-old dogma that sensation intensity grows as the logarithm of stimulus intensity (Fechner's law) The relation is not a logarithmic function at all On more than a score of sensory continua it has now been shown that apparent, or subjective, magnitude grows as a *power function* of stimulus intensity, and the exponents of the power function have been found to range from about 0 33 for brightness to about 3.5 for electric shock (60 cps) applied to the fingers There seems to exist, in other words, a simple and pervasive psychophysical law, a law that was once conjectured by Plateau and later abandoned by him, a law that is congenial not only to the mounting empirical evidence, but also to certain reasonable principles of theory construction (Luce, 1959) There will be more to say about the power law, but first a few words about Fechner

The misconception began when Fechner, in 1850, espoused the view that error itself provides a unit of measurement He called it the just noticeable difference (jnd) Under most circumstances the jnd is a statistical concept, a measure of the dispersion or variability of a discriminatory response, in short, a measure of error In deriving his logarithmic law, Fechner made the erroneous assumption that error is constant all up and down the psychological scale Although he was willing to assume that the stimulus level error is relative, that is, $\Delta\phi = k\phi$ (Weber's law), he assumed that at the psychological level $\Delta\psi$ equals a constant. From these two assumptions he derived the relation $\psi = k \log \phi$, and thereby caused much mischief

It is curious indeed that Fechner, a physicist, should have assumed that error, or variability of judgment, is constant all up and down the psychological continuum Most variables do not behave that way On the continua with which a physicist most often deals, error is usually not constant, but tends to vary with magnitude It is percentage error that typically stays constant precision can generally be stated as one part in so many

Suppose Fechner had taken this as his model, not only for the stimulus jnd $\Delta\phi$ but also for the subjective jnd $\Delta\psi$ He then could have written

$$\Delta\psi/\psi = k\Delta\phi/\phi$$

from which it would follow that the psychological magnitude $\psi$ is a power function of the physical magnitude $\phi$ But he fought off this suggestion when it was first made (by Brentano), and with Fechner's temporary victory psychophysics entered upon a period of futility during which there seemed to be no more interesting work to do than measure the jnd And the logarithmic law became "an idol of the den".

So much for the past Since the 1930s psychophysics has been staging a comeback New interest in the age old problem of sensory response has been kindled by the invention of procedures for assessing the over all input-output operating characteristics of the intact sensory system These methods show that sensory response grows according to a power law So rarely does it happen in the study of behavior that a simple relation can be shown to hold under many diverse kinds of stimulation, that the widespread invariance of the power law becomes a matter of large significance

## Measurement

The problem of the laws that govern the reactions of sentient organisms is intimately bound up with the problem of measurement Since the theory of measurement was thoroughly explored in another symposium (Stevens, 1959*b*), it need not divert us here It may be helpful, however, to refer to Table 1, which attempts a systematic classification of scales of measurement in a compact form (Stevens, 1946*a*, 1951) The four scales listed, *nominal*, *ordinal*, *interval*, and *ratio*, are those most commonly used in the business of science and all of them get involved in research on sensory communication

The nominal scale, the most general of the lot is not always thought of as a form of measurement, mainly because names or letters, rather than numbers, are most often employed to designate the categories or classes used in nominal scaling Yet this ubiquitous and important form of measurement goes on constantly, for it includes the process of identifying and classifying Mostly we take only a casual interest in such problems, but our interest has a way of turning into animated curiosity when it becomes a question of doing the detective work necessary to pin the proper labels on the functional parts of the central nervous system The identification of the "areas" associated with this or that sensory process constitutes a lively exercise in nominal scaling And needless to say, much of our scientific effort in this field never goes beyond the essential and basic nominal level The ordinary

### Table 1 A Classification of Scales of Measurement

Measurement is the assignment of numbers to objects or events according to rule The rules and the resulting kinds of scales are tabulated below The basic operations needed to create a given scale are all those listed in the second column down to and including the operation listed opposite the scale The third column gives the mathematical transformations that leave the scale form invariant Any number $x$ on a scale can be replaced by another number $x'$ where $x'$ is the function of $x$ listed in column 2 The fourth column lists, cumulatively downward, examples of statistics that show invariance under the transformations of column 3 (the mode, however, is invariant only for discrete variables)

| Scale | Basic empirical operations | Mathematical group-structure | Permissible statistics (invariantive) | Typical examples |
|---|---|---|---|---|
| Nominal | Determination of equality | Permutation group $x'=f(x)$ where $f(x)$ means any one-to-one substitution | Number of cases<br>Mode<br>"Information" measures<br>Contingency correlation | "Numbering" of football players<br>Assignment of type or model numbers to classes |
| Ordinal | Determination of greater or less | Isotonic group $x'=f(x)$ where $f(x)$ means any increasing monotonic function | Median<br>Percentiles<br>Order correlation (type 0 interpreted as a test of order) | Hardness of minerals<br>Grades of leather, lumber, wool, and so forth<br>Intelligence-test raw scores |
| Interval | Determination of the equality of intervals or of differences | Linear or affine group $x'=ax+b$ $a>0$ | Mean<br>Standard deviation<br>Order correlation (type I interpreted as $r$)<br>Product moment ($r$) | Temperature (Fahrenheit and Celsius)<br>Position on a line<br>Calendar time<br>Potential energy<br>Intelligence test "standard scores" (?) |
| Ratio | Determination of the equality of ratios | Similarity group $x'=cx$ $c>0$ | Geometric mean<br>Harmonic mean<br>Per cent variation | Length, density, numerosity, time intervals, work, and so forth<br>Temperature (Kelvin)<br>Loudness (sones)<br>Brightness (brils) |

determination of thresholds which involves the categorization of stimuli into classes (for example seen and not seen), is another important instance of nominal scaling (Stevens, 1958)

The key to the nature of the four kinds of scales lies in a powerful but simple principle the concept of invariance When we have carried out a series of empirical operations balancings comparisons, orderings, and so on, we assign a set of numbers to reflect the outcome of the operations This is the essence of measurement But what kind of measurement have we achieved? That depends on the answer to the decisive question in what ways can the scale numbers be transformed without loss of empirical information? As shown in Table 1, each of the scales has its group of permissible transformations

The ratio scale, the scale of greatest interest, allows only multiplication by a constant as when we change from inches to centimeters No more general transformation is allowed If an arbitrary constant were to be added to the measured diameters of a set of nerve fibers, for example, the resulting numbers would tell us less than we knew before We would have lost some valuable information namely our knowledge of the *ratios* among the fiber diameters Which fiber is twice as thick as some given fiber would now, with the altered scale values, be impossible to tell In general therefore, the more restricted are the admissible transformations, the more the scale is able to tell us

As regards the measurement of sensation the schema of Table 1 suggests that our aspiration should be to measure, where possible on a ratio scale This would call for assigning numbers to sensory magnitudes in such a way that anything more drastic than multiplication by a constant would result in a loss of information Several variations on such a procedure have been elaborated (Stevens 1958) but before we consider the resulting scales certain distinctions need to be made (Some nominal scaling needs to be done!)

## Sensory Qualities

An obvious thing about sensations is that they differ in both kind and amount Sweet is different from sour, but both may vary from weak to strong The sensory qualities get named and classified (nominal scaling), but we try to measure the subjective intensities on higher order scales

The distinctive quality aroused by a given sensory excitation presents a baffling problem for which no plausible explanation is yet

available Why does a sound differ from a taste in the way it does? This qualitative aspect of the sensory world confronts us with a baffling succession of discontinuous leaps as we go from one sense modality to another, and no one seems to know why On the other hand, it is at precisely this level that the anatomist and the neurophysiologist join the game and perform some of their most effective work in tracing pathways for the various modalities, and even for some of the separate qualities within a modality Clearly these problems of topography need to be clarified before an understanding of the sensory mechanisms can be anchored in the soup and substance of neural process Connections by themselves may not explain it all, but connections are there, and it seems improbable that they count for nothing

## Two Kinds of Continua

Psychophysics progresses beyond the elementary task of naming sensory qualities as soon as it becomes concerned with sensations that appear to lie on a continuum of some sort A continuum seems clearly to be involved when sensations vary in strength or intensity, but certain other attributes of sensory response seem also to form continua in the ordinary sense of the term

It would greatly simplify the mission of psychophysics if all the sensory continua obeyed the same rules, and did so in an invariant fashion It turns out, however, that a basic distinction needs to be made between two kinds of continua, prothetic and metathetic Loudness, for example, is prothetic, pitch is metathetic An important difference between the psychophysical functions governing pitch and loudness is this the jnd for pitch represents a constant distance on the scale of subjective pitch, measured in *mels*, whereas the jnd for loudness represents an increasing distance on the subjective scale of loudness, measured in *sones* (Stevens and Volkmann, 1940) In other words, provided they are measured in subjective units, the jnd for pitch is constant, but the jnd for loudness grows rapidly larger as loudness is increased The uniformity of sensitivity or resolving power on the pitch continuum and the nonuniformity on the loudness continuum entail several other functional differences between pitch and loudness These are discussed elsewhere (Stevens, 1957*b*)

The prothetic continua (loudness, brightness, and subjective intensity in general) seem to be concerned with *how much* The metathetic continua (pitch apparent azimuth, apparent inclination) have

to do with *what kind* or *where* (position) Corresponding to these two functional classes there seem to be two basic physiological mechanisms Sensory discrimination can be mediated by either of two processes the one *additive* the other *substitutive* (Stevens 1946*b*) We detect for example an increase in loudness when excitation is added to excitation already present We detect a change in pitch when new excitation is substituted for excitation that has been removed Or to consider another modality we can tell when a light pressure changes to a strong pressure at a given point on the skin (addition of excitation) and we can also tell when a stimulus is moved from one to another location (substitution of excitation) Whether all perceptual continua that behave in the prothetic manner are mediated by additive physiological processes is not certain of course but in at least some instances it seems evident that the existence of two basic kinds of physiological mechanisms is reflected in the behavior of the psychological scales and functions which we construct from subjective measurements in the sensory domain

Most of what follows is concerned with prothetic continua for they seem the more interesting and well behaved It should be noted however that the pitch continuum provides an example of a rather exciting attempt to match up and thereby "explain" several psychophysical functions by means of a physiological substratum Position of maximal excitation on the basilar membrane appears to relate in a straightforward linear manner to several sensory functions including the mel scale of subjective pitch the jnd and the so called critical bandwidth (Békesy and Rosenblith 1951 Zwicker, Flottorp and Stevens 1957)

## Three Kinds of Sensory Measures

Three separate classes of sensory scales are distinguished (and sometimes confused) in psychophysics

1 *Discriminability scales* These are constructed in the tradition of Fechner or his modern counterpart Thurstone Some measure of jnd variability confusion or resolving power is employed as a unit and a scale is constructed by counting off such units

2 *Category scales (partition scales)* These are constructed by one or another variation on the procedure that Plateau invented when he required observers to partition a segment of a continuum into equal appearing intervals (Plateau had eight artists paint a gray that seemed to be halfway between black and white) Bisection is

one partitioning procedure, asking a listener to assign a series of tones to $n$ equally spaced categories is another

3 *Magnitude scales* These are ratio scales of apparent magnitude, constructed by one or another of four principal methods, of which "fractionation" is perhaps the best known and "magnitude estimation" the most useful (see Stevens, 1956*b*, 1959*b*) Under the method of magnitude estimation the observer simply estimates the apparent strength or intensity of his subjective impressions relative to a stand

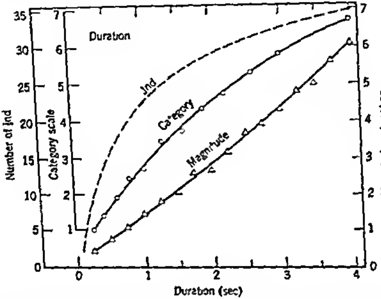



Fig 1 Three kinds of psychological measures of apparent duration *Triangles* mean magnitude estimations by 12 observers who judged the apparent durations of white noises. *Circles* mean category judgments by 16 observers on a scale from 1 to 7 The two end stimuli (0.25 and 4.0 sec) were presented at the out set to indicate the range and each observer twice judged each duration on a 7 point scale *Dashed curve* discriminability scale obtained by counting off jnd.

ard, or modulus, set either by himself or by the experimenter The power functions obtained by this procedure can, and indeed should, be validated by direct cross modality matches—a procedure that does not require the observer to make numerical estimations

An important difference between prothetic and metathetic continua is this on metathetic continua all three kinds of scales tend to be linearly related one to another on prothetic continua the three kinds of scales are nonlinearly related (Stevens and Galanter, 1957, Stevens, 1959*c*) Typical examples of the relations among the three kinds of scales on prothetic continua are shown in Fig. 1, for apparent

duration (of a noise), and in Fig 2, for apparent intensity of vibration applied to the fingertip On all prothetic continua the magnitude scale is a power function, the discriminability (jnd) scale approximates a logarithmic function, and the *category scale assumes a form* intermediate between the other two Over the different sense modalities, these relations among the three scales are strikingly invariant, they constitute one of the really stable aspects of psychophysics

Of the three kinds of measures shown in Figs 1 and 2, the one that seems most directly related to the over all input output function of a

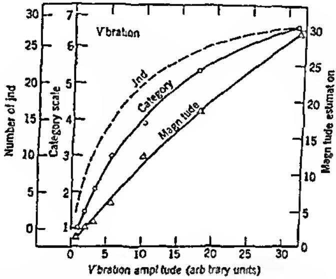



Fig 2 Three kinds of psychological measures of the apparent intensity of a 60 cycle vibration applied to the finger tip Procedures were essentially similar to those for Fig 1 For details see Stevens (1959*d*)

sensory system is the magnitude scale The scale obtained by counting off jnd *is really only that* At most *it tells us how resolving power varies with stimulus magnitude* The *category scale* is *at best only* an interval scale on which the zero point is arbitrary It is not a ratio scale But since it is nonlinearly related to the ratio scale of apparent magnitude, the category scale turns out, in fact, to be not even a good interval scale The reasons for the curvature of the category scale have been discussed elsewhere (Stevens and Galanter, 1957), but, roughly speaking it is as though the observer, when he tries to partition a continuum into equal intervals, finds himself biased by the fact that a given difference at the low end of the scale is more noticeable or impressive than the same difference at the high end of the scale

This asymmetry is not present on metathetic continua, and therefore the category scale is not systematically curved

## Operating Characteristics

Sense organs serve as the transducers that convert the energies of the environment into neural form Like any transducer, each sense organ has its dynamic operating characteristic, defined by the input-output relation It is only recently that much attention has been paid to the dynamics of sensory function—the manner in which the sensory system responds to variations in input intensity. Future efforts in this direction promise interesting rewards, however, for the form of the over all dynamic process is now becoming more fully understood

Conceivably, of course, all sense organs could have the same operating characteristic All sensations would then grow at the same rate with increasing stimulus intensity That this is far from true can be readily verified by a simple comparison Note, for example, what happens when the luminance of a spot of light is doubled Then note what happens when a 60-cycle current passing through the fingers is doubled Doubling the luminance of a spot of light in a dark field has surprisingly little effect on its apparent brightness As estimated by the typical (median) observer, the apparent increase is only about 25 per cent. But doubling the current through the fingers makes the sensation of shock seem about ten times as strong The dynamic operating characteristics of these two sensory systems are clearly and dramatically different.

Closer investigation reveals, however, that both brightness and shock have a fundamental feature in common In both instances the psychological magnitude $\psi$ is related to the physical magnitude $\phi$ by

$$\psi = k\phi^n$$

The exponent $n$ has the value 0 33 for brightness and 3.5 for shock The value of $k$ depends merely on one's choice of units As will be shown below, the physical measure used to express $\phi$ needs to take account of threshold.

The power function has the convenient feature that in log log coordinates it plots as a straight line whose slope is equal to the value of the exponent Figure 3 illustrates this fact and shows how the slow growth of brightness contrasts with the rapid growth of electric shock Also included for comparison is the function obtained by

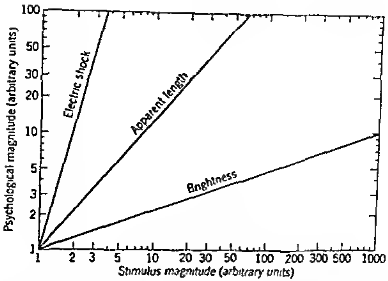



Fig. 3. Scales of apparent magnitude for three prothetic continua plotted in log-log coordinates. The slope of the line corresponds to the exponent of the power function governing the growth of the psychological magnitude

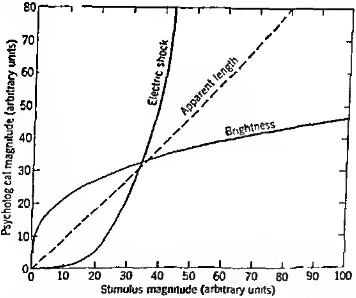



Fig. 4. In linear coordinates the subjective magnitude functions are concave upward or downward depending on whether the power function exponent is greater or less than 1.0

asking observers to make magnitude estimations of the apparent length of various lines. Here, as we should expect, the slope (exponent) of the function is not very different from 1.0. This is another way

of saying that to most people a length of 100 centimeters looks about twice as long as a length of 50 centimeters

The same three functions shown in Fig 3 are plotted in linear coordinates in Fig 4 The function for apparent length is almost a straight line (exponent about 1 1), but electric shock grows as an accelerating function and brightness as a decelerating function

### Exponents

The number of prothetic continua on which the psychophysical power law has been shown to hold to at least a first-order approximation now exceeds two dozen In the author's experience, there appears to be no exception (Hence the temerity of calling it a *law*)

Table 2 lists the exponents of the power functions for some of the continua explored thus far Although this table extends and revises the list presented earlier (Stevens, 1957*b*), it must still be regarded as tentative and incomplete, for there is virtually no limit to the number of different combinations of sense organs and stimuli that are waiting to be studied.

All the exponents in Table 2 were determined by the method of magnitude estimation Many of them have been confirmed in other laboratories and by other methods, such as fractionation Many of them, as we shall see, have also been validated by cross modality intercomparisons Nevertheless, it must be understood that the exact value of an exponent is difficult to determine with precision, and some of those listed in Table 2 must be regarded as a first approximation only In all cases, of course, the exponent represents an average value and is not necessarily appropriate to a particular individual At least ten observers were used to determine each of the exponents in Table 2, *although some exponents (for example, loudness, brightness, lifted weights)* have been determined in several laboratories and on large numbers of observers

The particular version of the method of magnitude estimation used in our most recent experiments—the one arrived at after some years of trial and error—is extremely simple In an experiment on loudness, for example, the procedure may be as follows The experimenter presents a "standard" sound of moderate intensity and tells the observer to consider its loudness to have the value of "10" The experimenter then presents in irregular order a series of intensities above and below the standard and instructs the observer to assign to each

stimulus a number proportional to the apparent loudness In other words, the question is if the standard is 10, what is each of the other stimuli? The observer is told to use any numbers that seem appro priate, fractions, decimals, or whole numbers, and to judge each stimulus as *he* hears it The standard is usually presented only at the

**Table 2. Representative Exponents of the Power Functions Relating Psychological Magnitude to Stimulus Magnitude on Prothetic Continua**

| Continuum | Exponent | Stimulus conditions |
|---|---|---|
| Loudness | 0 6 | Binaural |
| Loudness | 0 54 | Monaural |
| Br ghtness | 0 33 | 5° target—dark adapted eye |
| Brightness | 0 5 | Point source—dark adapted eye |
| Lightness | 1 2 | Reflectance of gray papers |
| Smell | 0 55 | Coffee odor |
| Smell | 0 6 | Heptane |
| Taste | 0 8 | Saccharine |
| Taste | 1 3 | Sucrose |
| Taste | 1 3 | Salt |
| Temperature | 1 0 | Cold—on arm |
| Temperature | 1 6 | Warmth—on arm |
| Vibration | 0 95 | 60 cps—on finger |
| Vibration | 0 6 | 250 cps—on finger |
| Duration | 1 1 | White noise stimulus |
| Repetition rate | 1 0 | Light sound, touch and shocks |
| Finger span | 1 3 | Thickness of wood blocks |
| Pressure on palm | 1 1 | Static force on skin |
| Heaviness | 1 45 | Lifted weights |
| Force of handgrip | 1 7 | Precision hand dynamometer |
| Autophonic level | 1 1 | Sound pressure of vocalization |
| Electric shock | 3 5 | 60 cps through fingers |

beginning of the series although a stimulus having the same intensity as the standard may appear as one of the stimuli to be judged along with the others With a series of six to ten stimuli each stimulus is usually presented twice, but the order of the stimuli is made different for each observer In the averaging of the data from a group of observers it is usual to compute the geometric means of the estimates, although sometimes the median provides a more representative measure Since the distributions of responses are usually skewed the arithmetic mean is seldom an appropriate statistic

## Cross-Modality Comparisons

Few scientists fail to sense an uneasy concern about the foregoing procedure, which seems to rely merely on the observer's expression of opinion, and which seems also to depend on his having a moderately sophisticated understanding of the number system This is a proper concern, because naiveté about numbers, and especially about the concept of proportion, *certainly impedes* the ability of some observers to perform well in this kind of experiment. The matching of numbers to sensation intensity is not something that a person does with fine precision, or that he feels great certainty about, even though the typical graduate student can usually manage a consistent set of estimates

The interesting question, however, is not whether we are uneasy about the procedure, but whether the experiments on magnitude estimation can predict other empirical consequences that can be put to test. In particular, can we confirm the power law without asking observers to make any numerical estimations at all? If so, can we proceed to verify the relations among the exponents listed in Table 2? An affirmative answer to these questions is suggested by the results of a method in which the observer equates the apparent strengths of the sensations produced in two different modalities By means of such cross modality matches, made at various levels of stimulus intensity, an "equal sensation function" can be mapped out, and its form can be compared with the form predicted by the magnitude scales for the two modalities involved

If, given an appropriate choice of units, two modalities are governed by the equations

$$\psi_1 = \phi_1^m$$

and

$$\psi_2 = \phi_2^n$$

and if the subjective values $\psi_1$ and $\psi_2$ are equated by cross modality matches at various levels, then the resulting equal sensation function will have the form

$$\phi_1^m = \phi_2^n$$

In terms of logarithms

$$\log \phi_1 = n/m \log \phi_2$$

In other words, in log log coordinates the equal sensation function

should be a straight line whose slope is given by the ratio of the two exponents

The experimental question is whether observers can make cross modality matches, and whether their matches can, in fact be predicted from the ratio scales of apparent magnitude determined independently by magnitude estimation The ability of observers to make the simple judgment of apparent equality has been well established in other contexts Heterochromatic photometry and the mapping of equal loudness contours provide two well known examples of procedures that involve the judgment of apparent equality of sensory intensity—a judgment made in the presence of an obvious qualitative difference It is but a small step to extend these procedures to cross modality equations As a matter of fact, some cross modality equations seem less difficult than some equations within a single modality

In principle, of course, cross modality matches can be made between every sensory continuum and every other one Since this potential enterprise involves heroic numbers of experiments, only certain illustrative tests have been completed They are sufficient, however, to demonstrate the general validity of the ratio scales of subjective magnitude. A few of these cross modality experiments will be described.

#### *Loudness versus Vibration*

Two stimuli that are relatively easy to equate for apparent strength are sound and mechanical vibration The sound employed was a band of noise of moderately low frequency, and the vibration was a single frequency (60 cps) delivered to the end of the middle finger (Stevens, 1959*a*)

The matching of the apparent intensities of sound and vibration was carried out in two complementary experiments In one experiment the level of the sound was adjusted to match the vibration, in the other the level of the vibration was adjusted to match the sound The sound and vibration were presented simultaneously (In many experiments the stimuli have been presented successively for one reason or another ) Each of ten observers made two adjustments at each level in each experiment

The results are shown in Fig 5 The circles represent the means of the decibel levels to which the sound was adjusted and the squares represent the means of the decibel levels to which the vibration was

adjusted The coordinate scales are in decibels relative to the approximate thresholds of the two kinds of stimuli

The interesting point to note is that the slope of the line in Fig 5 is 0 6, which is close to the slope that is called for by the ratio of the exponents of the two magnitude functions It is also apparent that the relation is essentially linear, which is consistent with the fact that, over the ranges of the stimuli involved, both loudness and vibration are governed by power functions

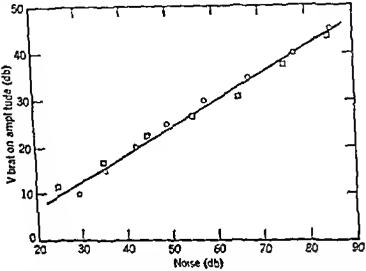



Fig 5 An equal sensation function relating 60-cycle vibration on the finger tip to the intensity of a band of noise The observers adjusted the loudness to match the vibration (circles) and the vibration to match the loudness (squares) The stimulus values are measured in terms of logarithmic scales (decibels)

The departure of some of the points from the straight line in Fig 5 is in large measure due to the interesting fact that, depending on which stimulus is adjusted, the slope turns out to be slightly different The situation is analogous to the two regression lines in a correlation plot. This "regression" or "centering tendency" is common, if not universal, in matching procedures, and it points up the desirability of a balanced design in which each stimulus is made to serve as both the standard and the variable (see Stevens, 1955*b*) The matching of loudness and vibration turned out to be surprisingly easy Some of the observers, who happened to have served in loudness matching experiments expressed the opinion that matching loudness to vibration seemed easier than matching the loudnesses of two tones of widely different pitch or quality (cf Stevens, 1956*a*) The consistency of the judgments seemed to bear this out.

two of the many experiments that have been performed to determine ratio scales of subjective magnitude for loudness and brightness

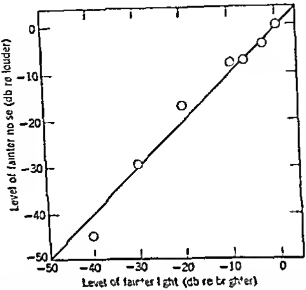
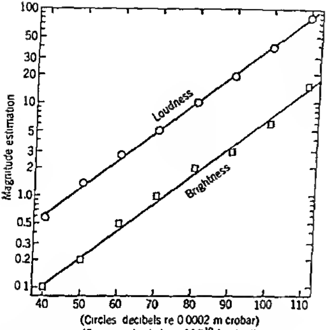



Fig. 6. Results of adjusting a loudness ratio to match an apparent brightness ratio defined by a pair of luminous circles. One of the circles was made dimmer than the other by the amount shown on the abscissa. The observer produced white noises by pressing one or the other of two keys, and he adjusted the level of one noise (ordinate) to make the loudness ratio seem equal to the brightness ratio The brighter light was about 99 db re $10^{-10}$ lambert, and the louder noise was about 92 db re 0 0002 dyne per square centimeter

It should be pointed out that the use of decibel scales simplifies the stimulus specification for vision and audition, and facilitates comparisons between their sensory dynamics The foregoing examples demonstrate some of these advantages Although the application of decibel measures to visual stimuli is not yet common practice, there is much to recommend it (see S S Stevens, 1955*a*). As a matter of fact, except for the rigidities of professional custom, the application of the decibel notation to the measurement of light presents less difficulty than its application to sound, because the decibel is defined in terms of energy flow

$$N_{db} = 10 \log \frac{E_1}{E_0}$$

and it is only by a kind of bastardized extension that the decibel gets used with measures of sound pressure. The energy in a sound wave




7. *Median magnitude estimations for loudness and brightness.*
or the loudness of a 1000-cycle tone, each of 32 observers made 2 estimates ach level Since no standard modulus was designated, each observer chose own, and the resulting numerical estimates were transformed to a common ulus at the 80 db level
or brightness each of 28 dark adapted observers made 2 estimates of each ulus level The target subtended an angle of about 5 degrees and was illu ited for about 3 sec *Once at the beginning of each session the observer was* n a stimulus of 70 db (14 observers) or 80 db (14 observers) and told to it "10" The estimates were transformed to a common modulus at 70 db

roportional to the square of the sound pressure, but only under special conditions With light, on the other hand, we are con ed only with energy measures, relative or absolute, and there is eed to become entangled in measures that are nonlinearly related nergy.

### rce of Handgrip

ke any other sensation, the subjective impression of muscle ten- can be measured on a ratio scale of psychological magnitude queezing a precision dynamometer (Fig 8), an observer can uce a sensation of apparent force and at the same time activate l that indicates the actual force exerted Two pertinent questions themselves (1) How does the feeling of apparent force relate

indicator of other subjective magnitudes has led to even more exciting results Instead of asking observers to emit numbers in response to stimuli, we can ask them to emit squeezes of appropriate sizes In this manner, observers have matched apparent force to apparent sensory intensity on nine different continua and have produced the

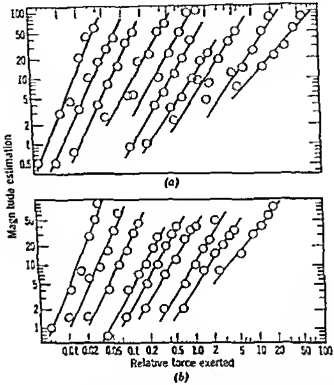



Fig 10. Functions for apparent force of handgrip obtained by the method of magnitude estimation. Each curve is for a single observer, and the position of the curve on the abscissa is arbitrary (*a*) Medians of 6 estimates by each observer using the dynamometer shown in Fig. 8 The forces estimated were 4, 10, 15, 22, 30, and 40 pounds. (*b*) Medians of 10 estimates by each observer using the more compliant dynamometer The forces estimated were 5, 11, 17, 23, 29, and 35 pounds.

results shown in Fig. 11 (J C Stevens, Mack, and S S Stevens, 1960, J C Stevens and S S Stevens, 1960)

Two points are immediately evident. All the data in Fig. 11 approximate power functions—straight lines in log log coordinates—and the slopes stand in the same order as the values of the exponents listed in Table 2. Less obvious but even more interesting is the exact numerical relation between the slopes determined by matching with handgrip and those determined by matching with numbers (that is

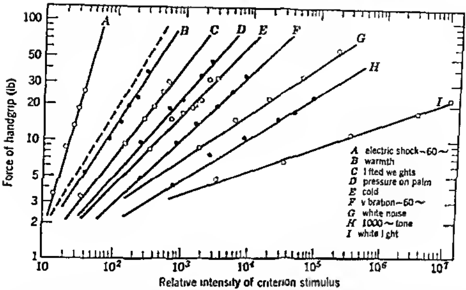



Fig 11. Equal sensation functions obtained by matching force of handgrip to various criterion stimuli Each point stands for the median force exerted by 10 or more observers to match the apparent intensity of a criterion stimulus The relative position of a function along the abscissa is arbitrary The dashed line shows a slope of 1 0 in these coordinates.

**Table 3. The Exponents (Slopes) of Equal-Sensation Functions, as Predicted from Ratio Scales of Subjective Magnitude, and as Obtained by Matching with Force of Handgrip**

| Ratio scale | | Scaling by means of handgrip | | |
|---|---|---|---|---|
| Continuum | Exponent of power function | Stimulus range | Predicted exponent | Obtained exponent |
| Electric shock (60-cycle current) | 3 5 | 0 29–0 72 milliampere | 2 06 | 2.13 |
| Temperature (warm) | 1 6 | 2.0–14.5°C above neutral temperature | 0 94 | 0 96 |
| *Heaviness of lifted weights* | 1 45 | 28–480 grams | 0 85 | 0 79 |
| Pressure on palm | 1 1 | 0 5–5 0 pounds | 0 65 | 0 67 |
| Temperature (cold) | 1 0 | 3 3–30 6°C below neutral temperature | 0 59 | 0 60 |
| 60-cycle vibration | 0 95 | 17–47 db re approximate threshold | 0 56 | 0.56 |
| Loudness of white noise | 0 0 | 55–95 db re 0 0002 dyne/cm² | 0 35 | 0 41 |
| Loudness of 1000-cycle tone | 0 0 | 47–87 db re 0 0002 dyne/cm² | 0 35 | 0.35 |
| Brightness of white light | 0 33 | 56–96 db re $10^{-10}$ lambert | 0.20 | 0.21 |

to say, magnitude estimation) Since the exponent for handgrip is approximately 1 7, we should expect that the exponent for a given continuum in Table 2 would be about 1 7 times as large as the slope of the corresponding line in Fig 11 How nearly this expectation is fulfilled is shown by the comparisons in Table 3 Despite the variability inherent in experiments of this sort, the agreement between the obtained and predicted exponent is generally satisfactory This agreement testifies with a certain eloquence to the basic validity of the ratio scales of sensory magnitude

### The Stimulus Scale

Except for the two continua, warm and cold, the physical stimuli of all the continua discussed above have been measured on the ordinary physical scales of amperes, grams, dynes, and so on This practice is sufficiently accurate for most purposes, but when we look more closely we see that the general form of the power law is

$$\psi = k(\phi - \phi_0)^n$$

where $\phi_0$ is a constant value corresponding to "threshold" For ranges of stimuli well above the minimum detectable level, the value of $\phi_0$ is usually negligible, but it assumes larger proportions when subjective scales are extended downward toward very low values

Temperature provides a clear and dramatic example of the importance of measuring stimuli in terms of the ratio scale of *distance* from threshold (J C Stevens and S S Stevens, 1960) The threshold for warmth when aluminum stimulators are applied to the inside of the forearm is about 305 7° above zero on the absolute scale (Kelvin) Compared to the short range of tolerable thermal stimuli, this is indeed a high threshold

As shown in Fig. 12 (log log plots), when apparent temperature is scaled by magnitude estimation and the results plotted against the Kelvin scale the data fall on a curve that is sharply concave downward When plotted in terms of degrees above the neutral or threshold value, however, the data fit a power function with an exponent of about 1 6 From these measurements it follows that the power function formula for subjective warmth $\psi_w$ is

$$\psi_w = k(T_K - 305\ 7)^{1\ 6}$$

where $T_K$ is absolute temperature.

In a similar type of experiment (aluminum stimulators applied to the arm), the formula for cold $\psi_c$ turned out to be

$$\psi_c = (304.2 - T_K)^{1.0}$$

The difference between the two values, 305.7 and 304.2, corresponding to $\phi_0$ is of no particular significance. It presumably means that the observers' average skin temperature was different in the two experiments. On most other continua the value of the additive

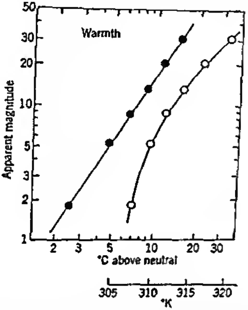



*Fig. 12.* Magnitude estimation of apparent warmth. Each point is the geometric mean of 36 estimates (12 observers). The upper abscissa, for the filled points, is a log scale of the difference in temperature (Celsius) between the stimulus and the "physiological zero." The lower abscissa, for the unfilled points, is a log scale of the absolute temperature (Kelvin).

constant $\phi_0$ is small relative to the usable stimulus range. Nevertheless, in two instances a revision of the stimulus scale designed to take explicit account of $\phi_0$ has transformed otherwise wayward data into well behaved power functions. The scale for tactile vibration (60 cps) applied to the arm was corrected in this manner (Stevens, 1959*d*), and a similar treatment was applied to the loudness scale by Scharf and J. C. Stevens (in press). As Luce (1959) has pointed out, the use of an additive constant to bring the zero of the physical scale into coincidence with the zero of the psychological scale is a proper generalization of the power function law. (Differences on a

ratio scale constitute a ratio scale, as do also differences on an interval scale )

In calling $\phi_0$ the "threshold" value, we raise a problem concerning precisely what is meant by the term threshold. It is not necessarily the threshold as measured in some arbitrary manner under arbitrary conditions Rather it should probably be thought of as the "effective" threshold that obtains at the time and under the conditions of the experiment in which the magnitude scale is determined Needless to say, this "effective" threshold cannot be measured very precisely Consequently, it becomes expedient to take as the value of $\phi_0$ the constant value whose subtraction from the stimulus values succeeds in rectifying the log log plot of the magnitude function Provided the constant value so chosen is a reasonable threshold value, this procedure seems justified At any rate, it has worked well for the four continua, vibration, loudness, warmth, and cold

## Variability

Needless to say, the responses people make to sensory intensity are variable Although an exemplary picture of this variability is shown in Figs 9 and 10, a further statement is in order about it The statement will be brief, however, because the author confesses to a certain lack of enthusiasm for elaborate statistical analyses

By and large, the interquartile range encountered when groups of observers undertake magnitude estimation on intensitive continua is of the order of 0 2 to 0 3 log unit. (It may, of course, be lower for continua that are easy to judge ) This variability contains certain obvious components, however, the most important of which appear to be the following.

1 *Variability due to the observer's modulus, that is, his conception of the "standard"* Since we are concerned only with the *form* of the magnitude scale, this source of variability is of no concern When desired, it can be partialed out in one way or another, with a consequent reduction in the over all variability

This component of variability is especially evident in those experiments in which each observer is allowed to choose his own modulus (Stevens, 1956*b*) It also plays a prominent role in cross modality matches (Stevens 1959*a*, J C Stevens, Mack, and S S Stevens, 1960) Each observer for example, has his own conception of what force of handgrip matches what level of loudness, but the absolute values chosen by the observer are irrelevant so far as the form of the

equal sensation function is concerned It is only the relative values that matter Concretely, our main concern is with the slopes and not the intercepts of the functions in Figs 9 and 10

2 *Variability due to the observer's conception of a subjective ratio* In a method like fractionation or magnitude estimation, each person must make up his own mind about what he considers "half as bright," say, and not all observers arrive at the same conclusion (A plot showing an example of the variability encountered in halving and doubling may be found in Stevens, 1957a ) Nothing much can be done about this source of variability, except perhaps to try to avoid biases and constraints in the conditions of observation (see Stevens, 1956b)

3 *Variability due to differing sense organ operating characteristics* This source of variability is biologically the most interesting, but it is probably of only minor magnitude in a group of "normal" observers Nevertheless, in the hard of hearing ear or the night blind eye, it may be a factor of considerable consequence (The state of a sense organ like the eye is also changed, of course, in the process of adaptation ) In order to evaluate this "sense organ" factor, it may prove useful to apply a battery of cross modality matching tests A sufficient battery of these tests should prove capable, for example, of distinguishing the person with auditory recruitment from the person whose conception of a subjective loudness ratio is merely atypical

An interesting problem related to variability concerns the question of departures from the power function law Can we expect that the power law will always hold rigorously (provided, of course, no errors arise in our measurements), or should we look for second order deviations from it? The data of particular experiments sometimes depart from the power law, but in most instances it is not easy to determine whether these defections are due to artificial biases of one kind or another Nevertheless, since the possibility of genuine departures from the power law is a problem of basic moment an effort should be made to devise procedures of sufficient accuracy to settle the question The fact that the power law is closely approximated by so many data in so many different sense modalities adds interest and significance to any authentic departures from the power function form

### The Role of Transducers

The foregoing suggestion of a method for determining the individual loudness function in a hard of hearing ear assumes that the nature

of the sensory transducer largely determines the form of a magnitude function. An opposite assumption has often been made, however, to the effect that the magnitude function merely reflects how observers have learned in the past to associate sensory impressions with some known aspect of the physical stimulus. The "learning" explanation has recently been revived (Warren, 1958), and, under the name "physical correlate theory," it is alleged to provide a "basis for Stevens' empirical law" (Warren, Sersen, and Pores, 1958). If this theory were correct, it would presumably explain why the psychophysical law is a power function, but the evidence that learning accounts for all the exponents in Table 2 is mostly nonexistent. Familiarity with the stimulus may be a factor in people's judgments on some kinds of continua (although how one would prove it is hard to see), but many of the continua in Table 2 are quite unfamiliar to the typical observer—at least as regards measures of stimulus intensity. And especially difficult to conceive is how familiarity with the physical stimuli—even if the observers had such familiarity—could account for the results of cross modality matching like those shown in Fig. 11.

It seems rather more probable that the exponents are what they are because of the nature of the sensory transducers. It is likely, for example, that the exponents for light and sound are smaller than 1.0 because these sensory transducers behave essentially as "compressors"—a characteristic that enables them to handle the enormous dynamic ranges of stimulation to which they are subjected. At the other extreme, in the transduction process involved with electric current applied to the fingers, there is an operation of "expansion" in the sense that the psychological magnitude grows as an accelerating function of stimulus intensity, that is, the exponent is greater than 1.0. It seems quite improbable that the form of this function was "learned" by the observer.

It is an interesting question whether electrical stimulation of nerves other than those in the fingers would also exhibit an accelerating transduction characteristic. In a study of the "electrophonic effect" (Jones, Stevens, and Lurie, 1940), patients lacking tympanic membranes were stimulated by means of an electrode placed inside the middle-ear cavity. Although some patients heard pure tones, seven of the group heard only a buzzing noise whose quality was more-or less independent of the frequency of the stimulating current. Since it is certain that other nerves (for example, the facial and the vestibular) were occasionally stimulated in the course of these experiments, it seems safe to conclude that the auditory nerve was also sometimes directly affected by the current. Direct, unpatterned stimulation of

the auditory nerve fibers would account for the patient's hearing only a noise

Some of the patients noted a large change in loudness when only a small change was made in the stimulating current This effect was so striking that an attempt was made to measure the loudness change by comparing it with a *sound in the opposite* (normal) ear The outcome is shown in Fig 13 (for further explanation, see Stevens, Carton, and Shickman, 1958) Apparently if the auditory end organ

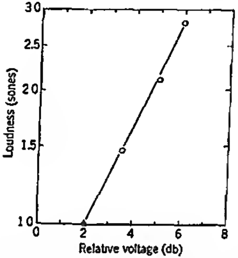



Fig 13 Showing the steep growth of loudness with increasing electric current applied to the auditory nerve of a patient whose eardrum had been removed The current was delivered by an electrode placed in the middle-ear cavity The exponent is about four times as large as the exponent obtained with acoustic stimulation

*is bypassed, and if a stimulating current acts directly* on the eighth nerve, a new transducer process becomes involved, and the function describing the growth of loudness acquires a radically different exponent The implication is that the "compression" observed when the normal ear is stimulated by sound waves is a function of the sense *organ, not of some higher center in the nervous system*

When it is discovered that two continua presumed to be rather similar are governed by different exponents (Table 2), one suspects that there may be basic differences in the transducer systems involved Two pairs of such continua are especially interesting warmth and cold, *and taste* and smell. Warmth and cold are interesting because the same stimulating device, applied to the same place on the arm produces two scales of sensory intensity, one for stimulus tempera

tures below neutral and one for temperatures above neutral (J C Stevens and S S Stevens, 1960) Not only do warmth and cold produce sensations of different quality, they also appear to do it by means of transducers with different operating characteristics The temperature sense is also unique in that the neutral or threshold point is the bottom of one stimulus scale (warmth) and the top of another (cold) Cold increases as the stimulus value decreases

Taste and smell are often classed together as chemical senses The mode of action of the stimulus for smell has been such a mystery, however, that mechanisms other than the bathing of end organs by chemical solutions have been hypothesized from time to time This state of affairs gives added significance to the obvious difference between the operating characteristics of the olfactory and gustatory systems For the several substances thus far tested, the exponents of the power functions for olfactory intensity have run from about 0.5 to 0 6 (Jones, 1958, Reese and Stevens, 1960) Earlier experiments on taste, with the method of fractionation, gave exponents of the order of 1.0 (Beebe Center and Waddell, 1948) The exponents for taste listed in Table 2 were obtained by Mary McLean in some exploratory experiments with the method of magnitude estimation. This work is still in progress, but there is little doubt that the exponents for taste are generally about twice as large as the exponents for smell. Does this difference in the dynamics of apparent intensity mean that two wholly different mechanisms underly the transduction processes in taste and smell?

## Summary

A central issue in the struggle to transform psychology into a science has long concerned the quantification of sensory magnitudes Fechner's creation of psychophysics was a monumental attempt to measure sensation, but the model as well as the method by which he hoped to achieve its quantification has turned out to be a vigorous stride in a wrong direction. Other models envisaging other methods, have lately achieved success in the mapping of quantitative relations on sensory continua.

The measurement of sensation in a manner useful to science has followed upon the clarification of several sticky issues that formerly thwarted the proper investigation of quantitative relations Progress has been made on the following points

1. Sensation has ceased to be regarded as a private mentalistic entity comprising one half of a metaphysical dualism, and has joined the class of other natural *constructs*, defined in terms of the operations used to denote and measure it. We study sensation by noting the behavior of organisms under the impact of energetic configurations (stimuli).

2. The concept of measurement has been broadened to include much more than the operation of counting, which was all there was to primitive measurement. Measurement is now conceived as the assignment of numbers to objects or events according to rule. The distinguishable rules, and the invariances consistent therewith, entail four classes of scales: *nominal, ordinal, interval,* and *ratio*. A fifth class, called *logarithmic interval*, is of some academic but little practical interest.

3. A basic distinction can be made between two kinds of sensory continua, prothetic and metathetic. The distinction rests on a set of functional criteria, but it is useful to think of the prothetic continua as those concerned with *how much* (intensity) and the metathetic continua as those concerned with *what* or *where* (quality). At the physiological level, many prothetic continua (loudness, brightness, and so forth) involve the addition of excitation to excitation, whereas some of the metathetic continua (pitch, apparent azimuth, inclination) involve the substitution of excitation for excitation.

4. Ratio scales of sensation, permitting a direct determination of the input-output characteristics of sensory systems, have been erected on prothetic continua by means of a variety of simple operations. The principal methods have involved (*a*) direct numerical estimations by the observer and (*b*) cross-modality comparisons in which the apparent strength of a sensation in one modality is made equal to a given sensation in another modality.

The outcome of these developments is a simple and attractive power law relating psychological magnitude to physical stimulus.

The formula is

$$\psi = k(\phi - \phi_0)^n$$

where $\phi_0$ is the effective threshold value. On some two dozen continua the exponent $n$ has been found to range from 0.33 for visual brightness to 3.5 for the subjective strength of electric current applied to the fingers. The generality and utility of this quantitative law may open new vistas in psychophysics and provide new insights into the roles played by the *sensory transducers*.

# 2

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# Some Aspects of Psychophysical Research

## A Note on Measurement

Although the problems studied in psychophysics are rather varied, one thing is central to all the work subsumed under this name That is the measurement of subjective variables In the present stage of psychophysical development we are concerned in particular with quantifying human experience on a relatively simple level, for example, measuring subjective brightness or pitch or perceived skin pressure This is not necessarily the whole thing, but it is fairly true for the present situation

The measurement technique, which is used in most of this work, has been developed mainly by S S Stevens and his co workers over a number of years Without going into any detail, I shall briefly characterize this sort of scaling I call it *direct* scaling of subjective variables, because the essential steps of the scaling procedure are implied in the experimental situation You may present a tone to the subject and tell him that the loudness of this standard tone is called 100 Now, in relation to this, what is the loudness of another tone of equal pitch? You may obtain the estimate 62, and this datum is one observation of the scale value of the second tone The two scale values are, by definition, on a ratio scale the ratio 62/100 should, according to the instructions, be equal to the subjective ratio of the second loudness to the loudness of the standard Of course, before the final scale can be constructed, you have to collect many observations and do some computational tricks with them, but fundamentally the situation is about as simple as outlined here

Even if this procedure seems to be quite straightforward, one might still be in some doubt about the metric properties of the resulting scale In an investigation carried out by Goude (1959) in this lab-

oratory, some fundamental properties of scales obtained by direct scaling methods were studied Results from two of Goude's experiments are shown in Fig 1 These experiments were designed to test the *additivity* of scale values In one part of the experiments (empty circles) the subjects were comparing single stimuli two at a time, as is commonly done in scaling In another part of the experiments (filled circles) the subjects were working with subjective *sums* of the

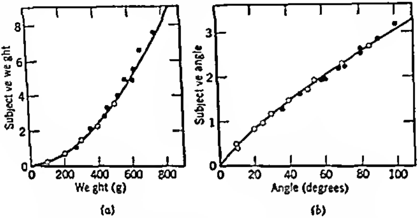


Fig 1 Results from an experiment on weight lifting (*a*) and another experiment on subjective magnitude of angles (*b*), carried out in order to test the additivity of scales constructed by direct ratio methods (Goude 1959) Unfilled circles represent scale values for single stimuli Filled circles represent scale values obtained when the subjects were working with subjective *sums* of subjective magnitudes In each experiment both sets of data exhibit the same trend that is closely approximated by the power functions represented by the curves

subjective magnitudes under consideration. The two sets of data thus obtained in each experiment clearly exhibit the same general trend and may well be approximated by the same curves, as shown in the graphs This is probably the first time that the fundamental metric property of additivity has been demonstrated in scales obtained by direct psychophysical methods of measurement. Results like these should increase our confidence in these methods

## Three Types of Problems

### Stimulus-response relations

It was Fechner's idea to investigate the relation between a subjective intensity and the intensity of the physical stimulation evoking the subjective response On the basis of Weber's law (which usually holds over a wide range) and the assumption that just noticeable

stimulus differences are subjectively equal (which in general they are definitely not, as we now know), he derived his famous logarithmic law which has ever since continued to appear in textbooks without ever being verified

In recent years, however, the *power function* has been found to describe the psychophysical relation very adequately for about twenty continua so far investigated Convincing evidence has been presented, especially by Stevens (1957) and Stevens and Galanter (1957) There is hardly a really convincing exception known to this rule We usually write the power function in the form

$$R = c(S + a)^n \qquad (1)$$

We have already seen two power functions fitted to the data in Figs 1*a* and *b* As a further illustration of this psychophysical law, I have chosen an experiment from our laboratory concerning the subjective brightness of monochromatic light of various wave lengths (Ekman, Eisler, and Kunnapas, 1960) In order to avoid confusion, the data have been divided into two graphs of Fig 2 The curves

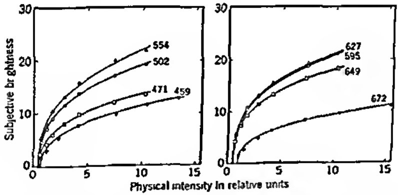


Fig 2. Brightness as a function of stimulus intensity for eight wave lengths. The circles and other symbols represent the scale values with a common unit of measurement In order to avoid confusion between nearly coinciding curves, the data are plotted and the curves drawn in two separate graphs The curves represent power functions For the various wave lengths the following functions are obtained

$$R_{459} = 4.93(S - 0.68)^{0.331}$$
$$R_{471} = 9.20(S - 0.60)^{0.338}$$
$$R_{502} = 8.94(S - 0.55)^{0.342}$$
$$R_{554} = 9.96(S - 0.50)^{0.346}$$
$$R_{595} = 9.71(S - 0.52)^{0.343}$$
$$R_{627} = 10.02(S - 0.51)^{0.334}$$
$$R_{649} = 8.30(S - 0.54)^{0.318}$$
$$R_{672} = 4.24(S - 0.95)^{0.363}$$

represent power functions fitted to the data, and there is a rather good agreement between these theoretical curves and the experimental data, which represent brightness values in terms of a ratio scale constructed by one of the direct methods mentioned above (magnitude estimation).

The parameter descriptive of the curvature of the function is the exponent This is about one third for all wave lengths, which is about the same order of magnitude as the exponent for white light. The parameter $c$ describes the relative brightness of a light of constant intensity and varying wave length And finally, the parameter $a$ can be considered to be related to the absolute threshold, although this relation may be complex (Ekman, 1959)

### *Psychophysiological relations*

By far the greater part of modern psychophysical work has been devoted to the classical problem of stimulus response relations The main outcome has been the power law with its rather remarkable generality This law is empirical and descriptive, and *per se* it does not tell us anything about the mechanisms responsible for the transformation it describes

In general, these mechanisms will have to be investigated on the psychophysiological level, but very little has been done so far It is well known that peripheral response processes often bear a logarithmic relation to stimulation Since the final subjective outcome is a power function of stimulation, we have to expect that the central process generating the subjective response is an antilogarithmic function of the peripheral process No such function has even been plotted, which I think should be a challenge to research workers in the neighboring fields of neurophysiology and psychophysics

However, we have some information about differential sensitivity which will have to be incorporated in any theory of the psychophysiological transformations of a stimulus intensity into a subjective magnitude such as brightness or heaviness or pain. This information may be briefly summarized as follows

1 Differential sensitivity, as measured on the stimulus continuum, is usually adequately described by the modified form of Weber's law

$$\Delta S = k_s S + a \qquad (2)$$

This has long been known and needs no particular illustration here

2. Differential sensitivity, as measured on the subjective continuum,

seems to follow the same principle

$$\Delta R = k_R R + b \tag{3}$$

This is less well known and deserves a few comments It was probably first pointed out by Harper and Stevens (1948) that the subjective counterpart of a just noticeable difference tends to increase with S In some recent studies from our laboratory we have tried to measure the just noticeable difference in terms of R, and Fig 3 shows the results for three sets of data The graphs verify Eq 3, they also suggest that the constant b may be negligible, but that question requires further investigation

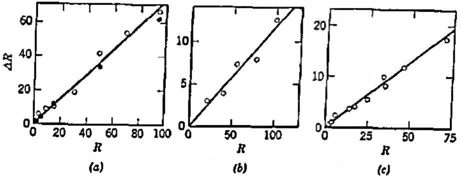


Fig 3. Just noticeable differences in subjective units $\Delta R$, plotted against subjective magnitude $R$ (*a*) values computed from data for lifted weights in two experiments by Oberlin (1936) transformed to a subjective scale, (*b*) results from an experiment on visually perceived velocity, and (*c*) results from an experiment on aurally perceived time (*Reproduced from Ekman, 1959*)

Let us for the moment accept both of the propositions stated above (Eqs 2 and 3) and see what we can do with them I think that the empirical information we now have may appear a little more intelligible if we look at it from the following points of view

1 The *discriminative response* appears to be essentially a peripheral process This would follow from the modification of Weber's law in Eq 2 and the demonstration that peripheral response is a logarithmic function of stimulus intensity When considered together, these relations mean that a *just noticeable difference* on the stimulus continuum has a counterpart in a constant increment on the continuum of *peripheral response* In other words, the derivation of Fechner's law would be valid at the level of peripheral response

2 The constant increment of peripheral response, however, corresponds to a subjective increment that is linearly related to the total

subjective magnitude This indicates a multiplicative transformation of peripheral response into *subjective response*, and this is precisely the antilogarithmic transformation we need to come out with the power function relating subjective magnitude to stimulus intensity

Perhaps we may tentatively conclude that *discrimination* and perception of *subjective magnitude* are psychophysiologically quite different processes, the latter being the final outcome of a step by step process of transformations

### *Intrasubjective relations*

Finally, I shall illustrate a type of problem that is more purely psychological than the two problems we have considered so far Until now we have been investigating psychological variables as functions of physical or physiological variables In the present context we are going to study relations *between* psychological variables

One such problem which has been studied for some time in our laboratory is concerned with the experience of *similarity* What function of their subjective attributes is subjective similarity between two stimuli? So far we have investigated this problem only for unidimensional continua, that is to say, we have allowed the two stimuli to vary only in one subjective dimension I shall illustrate this work by our first experiment, in which we studied the similarity of pure tones of varying pitch and equal loudness In one part of the experiment a pitch scale was constructed and in the second part of the experiment a scale of subjective similarity was obtained. It was now possible to investigate similarity as a function of pitch (Eisler and Ekman 1959) The result may be expressed by the equation

$$s_{ij} = \frac{R_i}{(R_i + R_j)/2}, \qquad (R_i \leq R_j) \tag{4}$$

where $s_{ij}$ varies from 0 (complete absence of similarity) to 1 (identity) Data from this experiment on pitch are shown in Fig 4, where the experimental measures of similarity are plotted against the theoretical values of similarity computed by Eq 4 from the experimental measures of pitch. In subsequent experiments the same equation has been shown to describe the mechanism of similarity also in the continua of brightness (the subjective continuum was defined as darkness) and visual area (Ekman, Goude, and Waern, 1961) as well as heaviness (Eisler 1960)

Since Eq 4 has been verified in four quite different perceptual continua it appears to possess a certain degree of generality It is one of the few strictly quantitative principles or "laws" known to describe

a psychological mechanism An outstanding feature of Eq 4 is the absence of empirical constants One thing I want to stress here is that the simplicity of this relation could be discovered only because it was investigated exclusively *within the subjective domain* Suppose that we had tried to investigate subjective similarity in terms of tonal frequency, other stimulus variables being equal At best we could have arrived at a rather complex empirical equation which it would

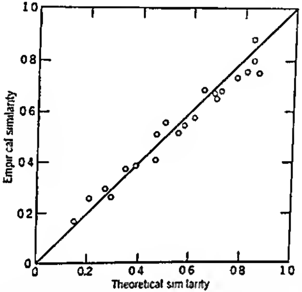


Fig 4 Experimental estimates of similarity plotted against theoretical values computed according to Eq 4 from a ratio scale of pitch. The data exhibit only a random fluctuation around the diagonal line representing perfect agreement Similar results have been obtained for brightness, visual area, and heaviness. (Reproduced from Eisler and Ekman, 1959 )

not have been possible to "understand" immediately, because pitch is a nonlinear function of frequency and because loudness would have been a second subjective variable in the experiment I think that these considerations are important, because they seem to indicate the possibility of discovering psychological mechanisms that may turn out to be rather simple when they are studied *on the proper level*

Let me add a few concluding comments on the similarity principle. My first guess in planning these experiments was that similarity might be a simple ratio between the two scale values ($s_{ij} = R_i/R_j$, where $R_i \leq R_j$) When the data were plotted, we immediately had to reject this hypothesis, and then Dr Eisler had a hard time fitting various functions until he found one that yielded acceptable results It was

first written as $1.98R_i/(R_i + R_j)$ We were fortunate in that 1.98 is pretty close to 2, and we could write Eq 4 without empirical constants, letting the factor 2 represent an averaging operation

Written in this form, Eq 4 tells us that the subjective similarity between two percepts varying in one subjective dimension is the ratio between the lower scale value and the arithmetic mean of the two scale values This interpretation is represented in the left hand part of Fig 5 It is certainly simple and, in a sense, intelligible But perhaps we can "understand" the perceptual process even better by writing the same equation in the form

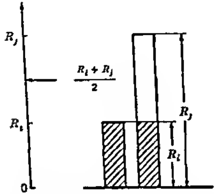


Fig 5 Illustrations of the similarity principle expressed by Eq 4. The left hand part of the graph represents Eq 4 and the right hand part the alternative form, Eq 4a. For explanations, see text.

$$s_{ij} = \frac{2R_i}{R_i + R_j} \qquad (4a)$$

which is represented in the right hand part of Fig. 5 Let us see how it can be interpreted

There are two different percepts of intensities $R_i$ and $R_j$, both present simultaneously as they are in the experimental situation. The similarity generating process does two things with this material (1) it counts off the part of $R_j$ that corresponds to $R_i$ (shadowed areas), and (2) it computes the *ratio between this common subjective magnitude $2R_i$ and the total subjective magnitude $R_i + R_j$* present in the experimental situation

Mathematically the two forms of Eq 4 are identical, but personally I now prefer the latter form, since it implies a more concrete model of the operation performed in the similarity generating process of a human nervous system What this operation would look like from the point of view of a brain physiologist I do not know, but it would certainly be interesting to know

### Extensions of Psychophysics

All the work I have discussed in this paper has been carried out by means of those direct psychophysical methods that I mentioned in the first section. The introduction of these methods by Stevens and his co-workers initiated the rapid development of modern psychophysics

These methods can be used only in experimentation with human subjects, since they require the subject to estimate relations between subjective magnitudes This becomes a serious limitation as soon as we want to extend our work to include animal experimentation. There are many reasons for expecting such extensions to become important within the near future Let me mention just two of them (1) Some of the psychophysiological work that seems desirable, from a psycho physical point of view, will necessarily have to be done with animals (2) Many intervening variables or hypothetical constructs (or whatever names they may go by) in learning theory are just the sort of things we are measuring every day in our human laboratories subjective variables like pain and similarity For well known reasons we usually want to investigate learning as dependent on such variables on the animal level, and accordingly we would need techniques for measuring them in animals too

For these reasons I would like to draw attention to another psycho physical tradition, initiated long ago by Thurstone (1927*a* *b*) on the basis of test theory and developed in quite different directions These methods may be called *indirect* methods, since they are based on a set of assumptions intervening between the experimental data and the final scale Experimentally these methods are sometimes even better adapted to animal than to human experimentation The kind of data for which they have been developed is in the form of right or wrong solutions, or of preference in a choice situation This is precisely the sort of data you obtain in maze performance and other situations in which animal behavior is studied The usefulness of these methods for measuring certain "underlying" not directly observable variables (response strength) in experiments on human learning has recently been convincingly demonstrated by Bjorkman (1958) The point I want to make here is that these methods might be used for measuring "subjective" variables (or whatever you may prefer to call them) in animals which cannot be asked what they experience (with human subjects it would be superstitious *not* to ask them) We shall have to make *some* assumptions, for example that the similarity principle is valid for the rat, and then we can proceed to investigate psycho logical mechanisms Let me mention here once more the possible *simplicity* of psychological relations when we investigate them on their proper (that is, psychological) level The important thing to do in order to discover a simple relation that may exist between per formance and motivation is to measure, say, amount of *thirst*—not hours of water deprivation

One obvious step now would be to scale subjective variables, with

human subjects, by the techniques of both sorts of psychophysical measurement, the direct and the indirect methods If in a number of such situations we obtain the same results, then we should feel more confidence in using the indirect methods in those cases where only these methods *can* be used

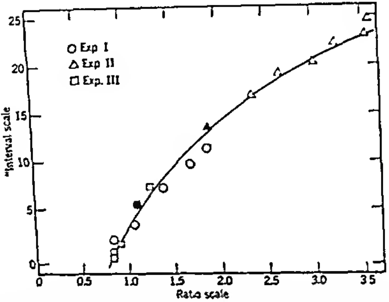


Fig 6. A comparison between two scales obtained for the esthetic value of handwriting specimens. The "interval scale" obtained by one of the indirect methods (pair comparisons) is represented by the ordinate and the ratio scale obtained by a direct method (ratio estimation) is represented by the abscissa. The curve represents the logarithmic relation to be expected if variability is proportional rather than constant.

Only few experiments of this sort have been undertaken. Those I know about were carried out in our laboratory (Bjorkman, 1959 Ekman, Kunnapas and Berglund, 1961) Some unpublished data from the latter study may serve as an illustration. Figure 6 shows results from experiments in which the esthetic value of handwriting specimens was measured. In this graph the interval scale $y$ constructed by an indirect Thurstone method (pair comparisons) is plotted against the ratio scale $x$ from a direct Stevens method (ratio estimation scale values computed according to Ekman, 1958) The "interval scale" was constructed on the assumption that variability is constant (Thurstone's Case V) If instead, it is proportional to the average scale value of the stimuli then it may be shown that $y \approx a + b \log x$

(cf Björkman, 1960) This function is graphed in Fig 6, and the fit of the data shows that the same scale (apart from an arbitrary zero point) may be constructed by the indirect method (on the revised assumption of proportional variability) as well as by the direct method Several studies are now being performed with the aim of investigating the general relations between direct and indirect scaling methods The ultimate purpose of these studies would be to find a common rationale, so that essentially the same scale can be constructed by either type of method

When more experiments of this sort have been carried out, we may proceed, with some confidence, to *measure* subjective pain, and thirst, and sexual drive, and brightness and—why not—esthetic value in infrahuman species Whether, on the animal level, you prefer to call them "underlying" or "subjective," is of minor concern

Finally it may be mentioned that even in human perception there are many psychological variables that cannot be directly observed The variable intensity of that process that manifests itself in certain figural reversals has recently been successfully studied by Künnapas (1961) by means of an indirect method Similar studies of the continuous, more or less rhythmical process which is responsible for fluctuations of attention" are now in progress

## Summary

This paper includes an introductory discussion of the metric properties of the presumed ratio scales obtained by "direct" psychophysical scaling methods Reference is made to some recent experiments demonstrating the additivity of such scales

Three main types of problems, which may be investigated by psychophysical methods, are outlined

1 Stimulus response relations, where response is a subjective variable, constitute a classical psychophysical problem formulated long ago by Fechner The general applicability of the power function to this kind of relation, which has been demonstrated especially by Stevens and his co workers, is pointed out and illustrated by a new experiment concerning the brightness of monochromatic light

2 The possibility of investigating certain psychophysiological relations is discussed On the basis of existing information it is tentatively concluded that stimulus discrimination and, on the other hand, perception of subjective magnitude may be psychophysiologically quite

different processes, the latter being the final outcome of a step-by-step process of transformations.

3. Attention is drawn to the possibility of investigating certain intra-subjective relations, relations between subjective variables. A series of experiments concerning subjective similarity is chosen as an illustration of this approach. It was demonstrated that similarity is a simple mathematical function—without empirical constants—of the subjective properties of the percepts being compared. These results seem to indicate the possibility of discovering psychological mechanisms which may turn out to be rather simple when they are studied on the proper—that is to say, subjective—level.

Finally some possible extensions of psychophysical work are discussed with special regard to animal experimentation. Measurement of "subjective" or perhaps rather "underlying" variables in animals will necessitate the use of "indirect" psychophysical methods of the type introduced by Thurstone, and it thus becomes an interesting task to study the relation between these and the "direct" methods generally used in human experimentation. Results from a preliminary experiment of this type are reported.

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# 3

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# On Psychophysiological Models

### *Preface*

This is not a written version of the talk I gave at the Symposium. In that talk, I summarized experimental data on information processing capabilities of human beings and described a model for categorizing patterns of stimulation. The data were intended to set boundary conditions on the communicative capabilities of the over-all human organism. The model was intended to focus attention on problems that arise in learning to handle redundant messages. It was evident from the discussion that, in order to bring the data and the model into resonance with the thinking of many of the members of the group, I would have to relate both data and model more closely than I did to actual, observable physiological processes. For the material presented, however, physiological interpretations are still to be formulated.

*Instead of insisting on the propaedeutic values of those data and that model, therefore, I am turning, in these written pages, to a smaller area in which it is possible to suggest fairly specific relations between parts of a model and observable neural processes. The conviction that guides my effort remains the same as it was before: a conviction that there are value and promise in psychophysiological models.*

Psychophysiological models seem to me to offer the possibility of bringing together in productive interaction (1) quantitative and qualitative findings of experimental and (even) clinical psychology, (2) substantive facts of neurophysiology and neuroanatomy, (3) abstract theorems and principles of mathematics and logic, and (4) insights and formulations achieved in the course of developing the technology of information processing and communication. Perhaps because I value that possibility very highly, it seems to me that it currently commands relatively little effort—relatively little, that is, as compared with efforts in purely psychological and purely physio

logical research or in psychophysiological research that does not involve mathematical models or ideas from communication theory, information theory, or the young field of "artificial intelligence." Happily, however, several papers presented at the Symposium and several parts of the discussion contributed strongly toward the development of, and, I hope, an ascendency for, psychophysiological models

### Procedure and Experience

Audio analgesia is a phenomenon only recently discovered and not yet well understood (Gardner and Licklider, 1959*a–c*) The essential fact is that a procedure involving acoustic stimulation but no conventional anesthetic or analgesic agents has made it possible for patients who previously had required nitrous oxide or a local anesthetic to undergo dental operations without serious pain or unpleasantness

The procedure is briefly this The patient wears earphones and controls his own acoustic stimulation through a control box held in his lap It has two control knobs, one for music and the other for a rushing, roaring sound derived from "white" noise At the beginning of the session, the patient selects the music he wants to hear—a stereophonic tape recording—and adjusts it to a volume suitable for ordinary listening When the dentist starts to work, or when his work causes any discomfort, the patient turns up the volume of the music As soon as there is a trace or forewarning of pain, the patient turns the noise knob It controls the level of the rushing, roaring "waterfall" sound. The over all sound pressure of the noise may be set as high as 116 decibels above 0 0002 microbar The intense noise drowns out or suppresses the pain in a great majority of cases

There is no longer any question of the efficacy of the procedure in dental operations Dr Wallace J Gardner, of Cambridge, has used the procedure with more than 1000 patients who previously required chemical agents The audio analgesia was completely effective with 65 per cent, and effective enough with another 25 per cent that no other agent was required and the acoustic procedure was preferred for subsequent visits Ten other dentists have now had fairly extensive experience with the procedure (more than 5000 patients in all), and their experience has paralleled Gardner's very closely The operations have included cavity preparation (drilling), grinding, and extraction. Gardner has had about 200 successful ex

tractions—including several multiple extractions—and no failures In short, in the dental office, the acoustic procedure appears genuinely to suppress pain, to provide analgesia in the sense of standard dictionary definitions of that word

Thus far, there is not enough experience with the procedure in nondental clinical situations to justify conclusions The available evidence, provided by physicians who have used the same sound producing equipment as was employed in the dental observations, is partly positive, partly negative The procedure was effective in several minor surgical operations but not in all It was wholly sufficient in five cases of labor and childbirth but required supplementation in three others It was ineffective in suppressing intractable pain associated with cancer

In the experimental laboratory, it is difficult to make a dramatic demonstration of suppression of pain by sound, but it is easy to create a discernible effect On the basis of preliminary experimentation, it appears that the factor of tension relaxation must be introduced into the laboratory situation before the degree of effectiveness observed in the dental office can be achieved (Weisz 1959) The same statement can be made, however, with reference to morphine and other pain relieving drugs There is little or no difference in effectiveness between morphine and placebo in a typically objective, analytical, laboratory context (Hill, et al, 1952)

## Psychological Characteristics of Audio Analgesia

Experience thus far gained has revealed several characteristics of audio analgesia for which one would like to have an explanation The characteristics are by no means precisely quantified, they are largely qualitative and clinical

1 In the absence of acoustic stimulation and conventional analgesic or anesthetic agent, pain tends to build up regeneratively during intervals of strong nociceptive stimulation

2 When nociceptive stimulation is withdrawn, after an interval of pain in the absence of acoustic stimulation and the conventional analgesic or anesthetic agents, the magnitude of the pain sensation decreases, but there is often a residual pain sensation, an after pain.

3 When an intense auditory stimulus is turned on and held for an interval at constant sound pressure level, the loudness rises rapidly to a maximum, then equilibrates or recedes to a relatively steady level ("perstimulatory fatigue")

4 Ordinarily, after the first 100 milliseconds, there is no positive after sensation in hearing, but a depression in sensitivity can be measured for a period following moderate or intense acoustic stimulation

5 In at least some situations, intense acoustic stimulation has a definite suppressive effect on the subjective magnitude of pain and on overt pain reactions

6 In general, effectiveness in suppressing pain increases with sound intensity, decreases with the intensity of the noxious stimulation

7 Relaxed patients experience more relief from pain than do tense patients The main role of the music in the procedure is to relax the patient before the operation is begun Except for hard-of hearing patients and children too young to manipulate the controls effectively, the patients with whom the audio procedure has been least effective have been patients who entered the situation in extreme tension or anxiety

8 In the experimental laboratory, in a psychophysical context, one can often detect a reduction in the pain produced by an electric shock or other noxious stimulus, but it is only a modest reduction, much less dramatic than the effects observed in clinical situations or even in laboratory situations in which the psychophysical context and set for careful observation are replaced by conditions favoring relaxation and diversion of attention

9 The procedure is more effective if the noise is turned up before pain develops than it is if the noise is withheld until pain is clearly present

10 Stimulation by intense noise appears to have a more or less persistent after effect on pain In some instances, after long or intense exposure, it has been possible for patients to undergo ordinarily painful operations without further presentation of noise In other instances, patients have been able to follow the gradual reappearance of pain during the course of seconds following presentation of a burst of noise

11 Pain may have some reciprocal effect on the loudness of noise or music, but it is not as marked as the effect of sound on pain

12 Once a pain has been suppressed it can sometimes be kept suppressed by a weaker sound than was at first required to over come it

13 Quite a few patients have fallen asleep while listening to music or noise during a dental operation Many have fallen asleep while still listening to music or noise in the interval immediately following an operation

14 Individual differences in use of the acoustic procedure are very great Some patients require intense noise, others use only moderate

levels and report that pain suppression is fully effective Some patients rely heavily on the music, turning it up to full volume instead of using noise Others use the noise control at every suggestion of pain

15 The several dentists who have used the audio procedure have had approximately the same percentage of success

16. Random noise is more effective in suppressing pain than other sounds tested, with the exception of random noise plus music

17. Although the high frequency components of "white" noise must be attenuated if one is to produce a sound that most patients will accept and willingly adjust to a high volume level, the upper cutoff frequency of the noise must not be made too low or effectiveness in suppressing pain will be lost

18 Some patients have reported that, while using the audio procedure, they felt something they could call pain, but that it didn't hurt the way pain ordinarily does"

19 Against certain types of pain, such as the pain produced by an electrodepilatory needle, photic stimulation appears to be more effective than acoustic stimulation (Baruch and Fox, 1959)

20 Distraction of attention from pain to something else appears to reduce pain

The items just listed do not provide a basis for curve fitting for the calculation of coefficients of correlation, for any of the activities usually associated with the development and testing of mathematical models Their qualitative nature may appear, indeed, to bar them from the realm of models Yet it seems worth while to try to organize the picture in some other way than merely to list the 20 statements

## "Explanations" of Audio Analgesia

Almost surely, several factors operate together in producing audio analgesia Their relative weights or importances vary from patient to patient and situation to situation. These seven seem usually to be the main ones (1) direct suppression of pain sensation, either the primary pain or the secondary elaboration of, or reaction to, the primary pain [reference is made here to Beecher's (1957) distinction], (2) relaxation, with consequent reduction of the elaboration reaction, (3) distraction of attention from pain, with consequent reduction of the apparent severity of the pain, (4) masking of the dentist's drill (in operations in which a drill is used), with consequent reduction in

the anxiety conditioned to the drill through earlier painful experiences, (5) improved communication with the dentist (through the changing levels of music and noise, which the dentist hears through his own earphones or monitor loudspeaker), with consequent reduction in fear, anxiety, or feeling of helplessness, (6) active role for the patient (who now can control a massive part of his experience in the dental chair), with consequent reduction in fear, anxiety, or feeling of helplessness, and (7) suggestion.

The *seven* factors have been cited, individually and collectively, as "explanations" of audio analgesia. Clearly, they are not explanatory in the reductionist sense, they do not describe any mechanism or process. Instead, they relate characteristics of the audio procedure to generalities that cover other situations than audio analgesia, and thus perhaps lend some plausibility to what might otherwise seem wholly implausible. This kind of "explanation" seems unsatisfactory, but it is about all that can be achieved without recourse to hypotheses that involve the neurophysiological substratum of behavior.

## Neurophysiological and Neuroanatomical Constraints on Models of Intersensory Interaction

Neurophysiological and neuroanatomical researches are making such rapid strides toward an understanding of interactions among sensory modalities in the reticular formation and related centers of the brain that it may soon be possible to specify precisely the loci involved in the suppression of pain by sound. For the time being, however, we may concentrate on process and neglect considerations that point to particular regions or nuclei, noting only that there is abundant opportunity, at levels from the upper boundary of the medulla to the cerebral cortex, for sound signals and pain signals to come together. What are some of the general neurophysiological and neuroanatomical considerations that may serve as guide lines or constraints in the development of a model of the interactive process?

1. The organization of the nervous system is characterized by focalized excitation or facilitation and diffuse inhibition or suppression. (The papers presented at this Symposium by Ratliff and Mountcastle provided beautiful examples of this principle of organization.) Where two or more sensory systems come into a common region but do not map themselves, point for point, into a common projection, therefore, we may expect the effects of one system on another to be inhibitory or suppressive rather than excitatory or facilitory.

2 It is necessary for the sake of stability that, on the average, inhibitory processes have higher gains than excitatory processes at high levels of activity, and that excitatory processes have higher gains than inhibitory processes at low levels of activity Otherwise, the brain would either "run down" into quiescence or undergo a regenerative "chain reaction" up to saturation

3 The temporal parameters of excitatory processes are usually shorter than those of inhibitory processes This fact may be related to the focalization of the former and the diffuseness of the latter

4 There is measurable activity in the neural substratum (for example, "spontaneous activity") even in the absence of contemporary stimulation and in the absence of (reliable) sensation (The word "reliable" is introduced to avoid argument here about thresholds ) It seems reasonable to postulate an underlying pain process that has continuous existence, though at low levels, during intervals in which there is ordinarily no report of pain

## A Psychophysiological Model of the Process Underlying Audio Analgesia

The interests of simplicity and generality pull in opposite directions. Because the facts to explain are so few and so qualitative, there is justification, at best, for only a very simple model. On the other hand, we may expect—we know, in fact, that there are—interactions among all the sense departments, and it seems restrictive to limit consideration to only hearing and pain, or to only a given pattern of facilitory and inhibitory coefficients The compromise has been to formulate a general model, one with a variable number $n$ of channels, each channel having variable parameters, but to exercise in the trials to be described here only a few specific realizations in which $n$ equals 2. The effect, therefore, is clearly on the side of simplicity It is, in fact, deliberate oversimplification, to represent a neural mechanism that involves several cascaded networks, each containing thousands of nerve cells characterized in part by all-or none response, by a mere pair of channels involving only a few continuous variables The object, however, is not to construct a brain. It is to construct a conceptual network (1) that is easy to understand, (2) that bears a recognizable (and potentially improvable) resemblance to part of the nervous system, and (3) that will behave in ways that manifest the characteristics of audio analgesia.

The model incorporates some, but by no means all, of the ideas

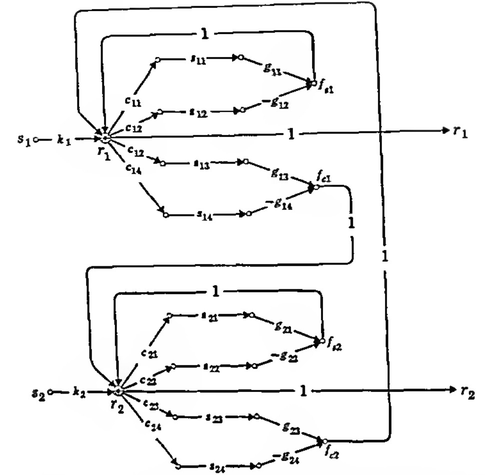



Fig. 1 Schematic diagram of the model. The nodes represent variables, the branches operations. The stimuli are $s_1$ (sound) and $s_2$ (pain). The responses are $r_1$ (loudness process) and $r_2$ (pain process). The variables $f_{s1}$, $f_{s2}$, $f_{c1}$, and $f_{c2}$ are self- and cross-feedbacks derived from $r_1$ and $r_2$ through the successive operations of clipping ($c_{ij}$), smoothing ($s_{ij}$), amplification ($\pm g_{ij}$), and addition. The over-all effect is to produce two stimulus-response channels, each subject to both positive and negative feedback from its own response and from the response of its neighbor.

about the pain mechanism that have been described by Hardy, Wolff, and Goodell (1952), Beecher (1957), and Melzack, Stotler, and Livingston (1958).

The model is illustrated schematically in Fig. 1. The stimulus or input is $s_1$. The response or output is $r_1$. The action of the network can be described most readily if we assume, for the moment, that the node marked with superposed + and × signs is simply an adder, as all the other nodes in fact are.

The response $r_1$ is formed by adding together the stimulus $s_1$, the self feedback signal $f_{s1}$, and the cross feedback signal $f_{c2}$. The self feedback signal $f_{s1}$ is formed from $r_1$ by clipping ($c_{11}$ and $c_{12}$), smoothing ($s_{11}$ and $s_{12}$), amplifying ($g_{11}$ and $-g_{12}$), and adding (at the node labeled $f_{s1}$). The characteristic of a typical clipper is

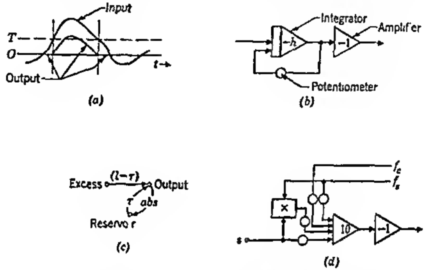
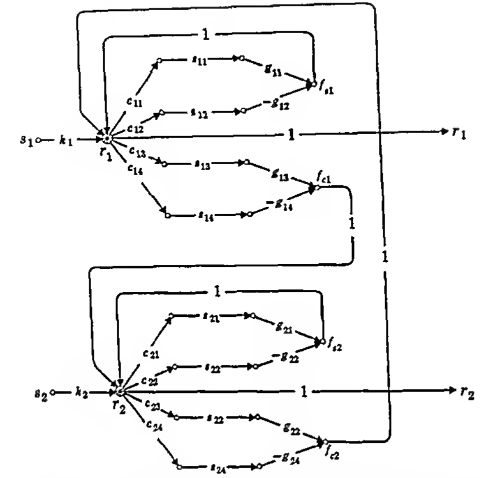



Fig 2 Details of operations in the model. (*a*) Behavior of a clipper that passes only the parts of the signal that exceed a preset threshold $T$. (*b*) Conventional analog integrator with negative feedback, equivalent to a resistance-capacitance smoothing filter, with time constant determined by the setting of the potentiometer. The amplifier following the integrator makes the gain of the network positive. (*c*) A digital smoothing circuit. The output is the weighted sum of the input (weight $1-\tau$) and the quantity (weight $\tau$) accumulated in the reservoir. The quantity in the reservoir is a remnant of past values of the input. The result is closely similar to that provided by (*b*). (*d*) The network that provides a weighted sum of addition and multiplication at the nodes marked by superposed + and × signs in Fig 1. Appropriate adjustment of the potentiometers provides the response $r = a(s + f_s + f_c) + (1 - a)(s f_c)$.

shown schematically in Fig 2*a*. The threshold $T_{12}$ of $c_{12}$ is higher than the threshold $T_{11}$ of $c_{11}$. That gives the positive feedback path the advantage at low signal levels. An analog smoother is illustrated in Fig 2*b*, and a digital smoother is illustrated in Fig 2*c*. In the latter, $\tau$ is a multiplicative coefficient and $(1-\tau)$ is its complement, *abs* is an operator that delays the signal one interval of calculation time and then replaces the signal by its absolute magnitude. Both Figs 2*b* and *c* approximate the action of a simple resistance capacitance smoothing filter. The time constant of $s_{12}$ is longer than that of $s_{11}$. That makes the negative feedback more sluggish than

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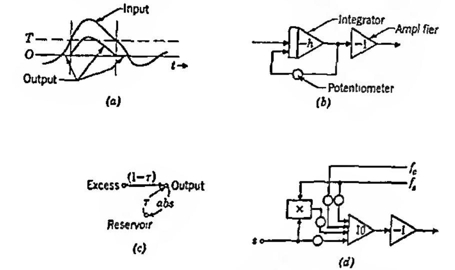


**Fig 2.** Details of operations in the model (*a*) Behavior of a clipper that passes only the parts of the signal that exceed a preset threshold $T$ (*b*) Conventional analog integrator with negative feedback, equivalent to a resistance-capacitance smoothing filter, with time constant determined by the setting of the potentiometer The amplifier following the integrator makes the gain of the network positive (*c*) A digital smoothing circuit. The output is the weighted sum of the input (weight $1-r$) and the quantity (weight $r$) accumulated in the reservoir The quantity in the reservoir is a remnant of past values of the input The result is closely similar to that provided by (*b*) (*d*) The network that provides a weighted sum of addition and multiplication at the nodes marked by superposed + and × signs in Fig 1 Appropriate adjustment of the potentiometers provides the response $r = a(s + f_s + f_c) + (1 - a)(sf_c)$

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the positive feedback. Finally, $g_{12}$ is greater than $g_{11}$. That gives the advantage of greater gain to the negative feedback paths when the signal level is much greater than the clipping thresholds.

The signals $f_{r}$, $f_{c1}$, and $f_{c2}$ are derived in ways that correspond directly to the one just described. We have in sum, therefore, both positive and negative feedback from each channel to itself and from each channel to every other. The only thing that remains to be described is the node with the superimposed + and × signs.

Consider two neural channels that come together and impinge upon a third. The response $z$ of the third is a function of the levels of activity $x$ and $y$ of the incoming two: $z = F(x, y)$. In what is perhaps the simplest concept, $F$ is the sum $z = x + y$. In another interpretation almost equally familiar, $F$ is the product $z = x \cdot y$. To achieve a helpful but limited degree of generality, we may combine the two notions linearly and let the equation $z = F(x, y)$ be $z = a(x + y) + (1 - a)(x \cdot y)$, with $0 \leqq a \leqq 1$. That is essentially the interpretation of $F$ used in the model. In the model, however, three "neural channels," not two, impinge upon the outgoing channel.

The interpretation actually employed in the model is shown in Fig. 2*d*. The three incoming signals are $s$, $f_{s}$, and $f_{c}$. The response $r$ of the outgoing channel is $a(s + f_{s} + f_{c}) + (1 - a)(s \cdot f_{s})$. That limits the nonlinear (multiplicative) action to the self feedback signal $f_{s}$ and the input $s$. To a degree controlled by $(1 - a)$, the self feedback signal turns a valve through which the input flows to yield the response. The input variable $s$ is never negative.

## Identifications between Variables of the Model and Variables of Audio Analgesia

The interpretation of the model is direct. The two channels are parts of the auditory and pain systems. The input variables $s_1$ and $s_2$ are the strengths of acoustic and nociceptive stimulation, respectively. The output variables $r_1$ and $r_2$ are the strengths of the sound and pain *processes*, respectively. The subjective magnitude of the sound (loudness in sones) is a monotonic, nondecreasing function of $r_1$, and the subjective magnitude of the pain (subjective painfulness in dols) is a monotonic nondecreasing function of $r_2$. For present purposes we may say that loudness $L$ is equal to $r_1 - c_1$ when $r_1 \geqq c_1$, and $L$ is equal to 0 when $r_1 \leqq c_1$, and we may say that subjective painfulness $P$ is equal to $r_2 - c_2$ when $r_2 \geqq c_2$, and $P$ is equal to 0 when $r_2 \leqq c_2$. To simplify things further, we may let $c_1 \cong 0$. For

the pain channel, however, it seems better to assume that there is no ordinarily reported pain until the pain process exceeds a threshold significantly above zero

The thing in the model that corresponds most directly to "level of tension" in a patient *is the sum of the feedback signals* Note that this is not a unitary thing Tension, as the word is used in clinical contexts, is a global term In the model, even oversimplified as it is, there are two "tensions" in the auditory system and two more in the pain system One member of each pair ("anxiety," perhaps) has a direct effect upon the gain of the channel, the other has only an indirect effect.

The clipping threshold $T_{21}$ associated with $c_{21}$ in the model bears a relation to tolerance for pain in the actual patient. If $T_{21}$ is high the regenerative growth of pain does not begin until the level of sub jective pain is fairly high, if $T_{21}$ is low, the regenerative build up begins at once The thresholds associated with the other clippers may be given corresponding interpretations

## Behavior of the Model in Response to Stimulation

The model has been realized in two forms a digital computer pro gram and an analog computer setup Because the digital computer is a small, slow machine, the digital program has been run in only a few configurations, all with $a = 0$, which specifies linearly additive combination at the nodes at which stimuli and feedbacks are com bined The digital program, however, can be changed from two channels to twenty by writing "20" on a typewriter, and it thus has the advantage of growth potential The analog computer set up pro duces results much faster It has been run with both linearly additive and partially multiplicative combinations at the crucial nodes

In describing the simulation tests, we shall refer to the variables as acoustic and nociceptive stimuli, sound and pain responses, and so on That seems preferable to the alternative of designating them always by letters because (1) it brings to the foreground the linkages between variables of the model and variables of the situation repre sented and (2) there seems to be little danger of confusion between the two realms of discourse

### *Behavior of the digital simulation*

The behavior of the digital program in a long run with three modes of stimulation is shown in Fig 3 The parameters of the model for this run are given in Table 1

For Fig. 3*a*, only ... ployed. The painful stimulus was applied first ... hich we may call 1 unit, then at 2 units, then at 4 units, and finally at 8 units. The

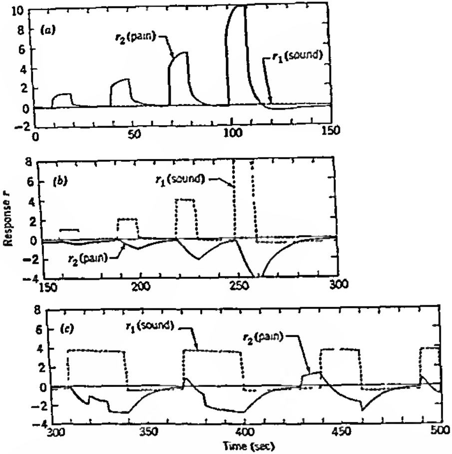


Fig. 3. Behavior of the digital simulation. (*a*) Responses to a series of four noxious stimuli. The stimuli occur at the intervals 9–19, 39–49, 69–79, and 99–109 sec. Their relative strengths are 1, 2, 4, and 8 (*b*) Responses to a corresponding series of four acoustic stimuli. Note the depression of the already subliminal pain process. In (*c*) acoustic and nociceptive stimuli are presented together The acoustic stimulus is on at strength 4 during intervals 309–339, 369–399, 439–459, and 489–499 sec. The noxious stimulus is on during intervals 319–329, 369–379, 429–459, and 489–499 sec.

responses of both the auditory and pain channels are shown The pain response rises rapidly as soon as the nociceptive stimulus is applied, continues to build up during the course of stimulation, and drops rapidly but not to zero level, when the stimulus is removed. The

**Table 1. Parameters of Digital Simulation for Tests Shown in Fig 3**

| $i$ | $a$ | $j$ | $k_j$ | $T_{ij}$ | $\tau_{ij}$ | $g_{ij}$ |
|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 1 0 | 0 0 | 0 7 | 3 0 |
| | | 2 | | 4 0 | 0 975 | 5 0 |
| | | 3 | | 1 0 | 0 9 | 0 3 |
| | | 4 | | 4 0 | 0 925 | 0 5 |
| 2 | 0 | 1 | 1 0 | 0 0 | 0 9 | 1 0 |
| | | 2 | | 1 0 | 0 975 | 5 0 |
| | | 3 | | 1 0 | 0 9 | 0 5 |
| | | 4 | | 0 5 | 0 9 | 10 0 |

nociceptive stimlus has a small effect on the loudness process A corresponding effect of actual pain on actual loudness might be made noticeable in a suitably designed psychoacoustic experiment In the dental situation, however, such a small suppressive effect would not be noticed

For Fig 3*b*, only acoustic stimulation was employed The applications are graded, as they were in Fig 3*a* While the stimulus is on, the loudness process holds almost a steady level When the stimulus is terminated, the loudness process falls to subzero values This is analogous to the "poststimulatory fatigue" observed in auditory tests (Caussé and Chavasse, 1947, Gardner, 1947, Luscher and Zwislocki, 1947, de Maré, 1939)

For Fig 3*c*, both acoustic and nociceptive stimulation were employed We may examine the effect of the sound on the pain by comparing Fig 3*c* with 3*a* It is the temporal course, rather than the magnitude, of the suppressive effect that is of primary interest [The effect can be made as marked as is desired, of course, by manipulating parameters of the model The magnitude of the effect observed with this particular configuration of parameter values (Table 1) is characteristic of a very successful application of the audio procedure to a favorable subject.] It is noteworthy that the effectiveness of the acoustic stimulation in suppressing pain is greatest when the acoustic stimulus is applied before the painful stimulus, and that there is a small "twinge" of pain at the beginning of stimulation when the two stimuli are applied simultaneously Corresponding effects are noted repeatedly in dental operations

### Behavior of the analog simulation

Figure 4 shows a sample of the behavior of the analog simulation Table 2 gives the corresponding parameters Throughout the record,

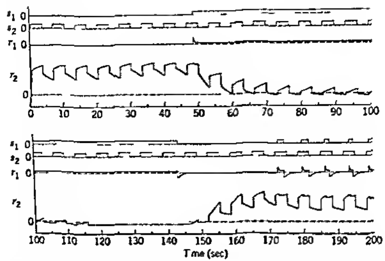


Fig 4 Behavior of the analog simulation. The chart shows two contiguous 100-sec intervals of stimulation and response The acoustic and nociceptive stimuli are marked $s_1$ and $s_2$, respectively, and the corresponding responses, $r_1$ and $r_2$

**Table 2. Parameters of Analog Simulation for Tests Shown in Fig 4**

| $i$ | $a$ | $j$ | $k_i$ | $T_{ij}$ | $\tau_{ij}$ | $g_{ij}$ |
|---|---|---|---|---|---|---|
| 1 | 0 1 | 1 | 1 0 | 0 5 | 0 5 | 1 0 |
| | | 2 | 1 0 | 4 0 | 1 0 | 1 0 |
| | | 3 | 1 0 | 0 5 | 0 5 | 0 5 |
| | | 4 | 1 0 | 4 0 | 1 0 | 4 0 |
| 2 | 0 1 | 1 | 1 0 | 0 5 | 1 0 | 1 0 |
| | | 2 | 1 0 | 4 0 | 10 0 | 1 0 |
| | | 3 | 1 0 | 0 5 | 1 0 | 0 0 |
| | | 4 | 1 0 | 4.0 | 10 0 | 0 5 |

a fairly strong nociceptive stimulus is turned on and off periodically. A relatively weak acoustic stimulus is turned on for a prolonged interval covering the middle portion of the sample and, again, for short intervals near the end of the sample With the parameters of Table 2, the loudness process equilibrates rapidly and then holds a steady level A corresponding temporal course has been observed for actual loudness by Hood (1955) and Egan (1955), in psychoacoustic experiments When the stimulus is terminated, the loudness process falls to subzero values

The suppressive effect of the acoustic stimulation appears on two quite different time scales The gradual, progressive suppression produced by the long presentation of the acoustic stimulus is clearly

evident in the middle part of the record A more immediate, but less marked, effect can be seen at the onset of acoustic stimulation The latter effect is clearest in the traces near the end of the record, where the sound is turned on and off during each of several bursts of pain

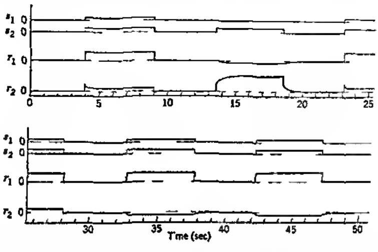


Fig 5 Behavior of the analog simulation The layout is similar to that of Fig 4 Compare the second pain response during quiet with the first and third during noise. The fourth and fifth pain responses are entirely suppressed.

stimulation The great difference between the effect producible in a moment and the effect that can build up over a period of time should be borne in mind

Figure 5 shows another sample of the behavior of the analog simulation, this time with the parameters of Table 3 In Fig 5 the acoustic

**Table 3 Parameters of Analog Simulation for Tests Shown in Fig 5**

| $i$ | $a$ | $j$ | $k_{ij}$ | $T_{ij}$ | $\tau_{ij}$ | $g_{ij}$ |
|---|---|---|---|---|---|---|
| 1 | 0 1 | 1 | 1 0 | 0 5 | 0 5 | 1 0 |
| | | 2 | 1 0 | 4 0 | 1 0 | 1 0 |
| | | 3 | 1 0 | 0 5 | 0 5 | 0 5 |
| | | 4 | 1 0 | 4 0 | 1 0 | 5 0 |
| 2 | 0 1 | 1 | 1 0 | 0 5 | 1 0 | 1 0 |
| | | 2 | 1 0 | 4 0 | 10 0 | 1 0 |
| | | 3 | 1.0 | 0 5 | 1 0 | 0 0 |
| | | 4 | 1 0 | 4 0 | 10 0 | 1 0 |

stimulus is not strong enough relative to the painful stimulus, to suppress the pain process rapidly

The painful stimulus and the acoustic stimulus are presented exactly together in every stimulus cycle but the second In the second, the acoustic stimulus is withheld The pain is clearly worse in the absence than in the presence of the sound In the latter part of the record, the successive presentations of the sound gradually suppress

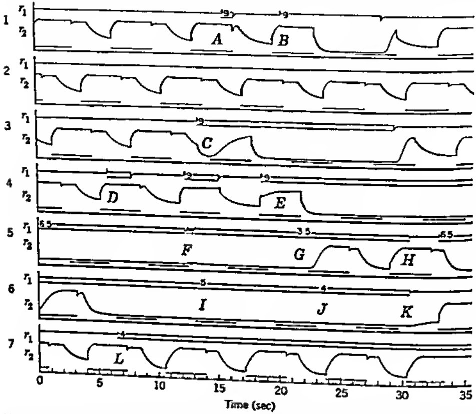


Fig. 6. Behavior of the analog simulation. The stimulus presentations are marked, in this figure, by lines below the responses The intensity of the painful stimulus, when on, is constant. The relative strengths of the acoustic stimuli are specified by numbers superposed upon the record In addition to effects shown in earlier figures, this figure illustrates how the effectiveness with which sound suppresses pain depends upon the state of relaxation tension at the time the sound is applied.

the pain process but never entirely overcome it. The pain process has a discernible effect upon the auditory process, but again it is not marked.

Essential characteristics of audio analgesia not yet discussed are exhibited in the behavior of the analog model with the parameters given in Table 4 Figure 6 shows the results of a long run with those parameters Throughout the record, a very intense nociceptive stimu-

Table 4 Parameters of Analog Simulation for Tests Shown in Fig 6

| $i$ | $a$ | $j$ | $k_{ij}$ | $T_{ij}$ | $\tau_{ij}$ | $g_{ij}$ |
|---|---|---|---|---|---|---|
| 1 | 0 3 | 1 | 1 0 | 0 5 | 0 5 | 1 0 |
| | | 2 | 1 0 | 4 0 | 2 0 | 1 0 |
| | | 3 | 1 0 | 0 5 | 0 5 | 0 5 |
| | | 4 | 1 0 | 4 0 | 2 0 | 4 0 |
| 2 | 0 3 | 1 | 1 0 | 0 5 | 2 0 | 1 0 |
| | | 2 | 1 0 | 4 0 | 10 0 | 1 0 |
| | | 3 | 1 0 | 0 5 | 2 0 | 0 0 |
| | | 4 | 1 0 | 4.0 | 10 0 | 0 0 |

lus goes on and off periodically Its intensity while on is constant An acoustic stimulus also goes on and off, but at irregular intervals The intensity of the acoustic stimulus is varied several times during the run

At the beginning of line 1 in Fig 6, the acoustic stimulus is off The pain process is going through cyclic variations in which it builds up to quasi saturation when the noxious stimulus is on and recovers partially while the noxious stimulus is off The quasi saturation level is determined by the interplay of the positive and negative feedbacks Each time the painful stimulation is removed, the pain process drops suddenly, but only for a short time Then for a short time it holds a high level (again, determined by the interplay of the feedback signals), and then it declines exponentially toward its quiescent operating point.

A brief burst of intense sound (intensity 9) at A in Fig 6 has a barely discernible immediate effect on the pain process, the effect on the recovery phase is somewhat more evident.

The intense sound stimulus beginning at $B$ has only a minor effect during the pain stimulus interval because of the great intensity of the pain stimulus As soon as the pain stimulus is removed, however, the sound drives the pain process down rapidly Note, particularly, that, once the pain process has been suppressed, even the strong nociceptive stimulus is unable to break through the suppression provided by the sound Only when the sound is turned off does the pain process rise Then, by the second cycle, it is back to its quasi saturation and partial recovery behavior That behavior continues through eight pain cycles (lines 2 and 3) without further acoustic stimulation

When the sound is turned on again at $C$ (intensity 9), the painful stimulus is off The sound rapidly suppresses the pain process, but the painful stimulus comes back on before full suppression is achieved.

The burst of pain stimulation elevates the pain process but does not succeed in raising it to quasi saturation because it is working against the influence of the sound During the second pain stimulusfree interval, the suppressive effect of the sound fully depletes the pain process, and there is no more pain activity until the sound is turned off

Beginning at *D*, the record illustrates effects of bursts of sound presented during the intervals of painful stimulation As before, the effects are noticeable mainly in the recovery intervals

Thus far, during the run, the acoustic stimulus has been either at intensity 9 or at intensity 0 At *E*, shortly after an onset of the pain stimulus, the acoustic stimulus is turned on again at intensity 9 By the second pain cycle, it has fully suppressed the pain process Then, at the beginning of line 5, the strength of the acoustic stimulus is reduced to 6.5 Even at the reduced level, it is effective in preventing the rise of the pain process during the following cycles During one of them, at *F*, there was difficulty with an "earphone lead," and the pain process almost was able to resume activity The difficulty was corrected quickly, however, and the pain process subsided.

At *G*, the acoustic stimulus was again reduced in strength, to 3.5 At this new level, the suppressive effect was not great enough to hold down the pain process, which returned to its cycle of quasi saturation and partial recovery

Next, at *H*, the acoustic stimulus was turned off, and then back on again at intensity 6.5 As before, it gradually overcame the pain and reduced the pain process to near zero level. Again the souod intensity was reduced—to 5 at *I* and then to 4 at *J*—and again the weaker acoustic stimulation was effective in holding the pain process in abeyance through several cycles When the weaker acoustic stimulus was then turned off at *K*, the pain process resumed its familiar course

Note, particularly, now, at *L*, that when the weaker acoustic stimulus was turned on again, it was unable to have much effect on the pain It could hold the pain process down when it caught the pain process in a suppressed state (*J*), but it could not overcome the pain process when the latter was fully active (*L*) The run ends with several cycles of quasi saturation and partial recovery despite the presence of the not quite-sufficient acoustic stimulation.

## Evaluotion of the Model

The model is admittedly preliminary, tentative, and oversimplified Little comes out of it that was not put into it other than the demon

stration that the network actually does what intuition says it must do Of course, the model can relate the behavior to the parameters more accurately than an intuitive grasp of the process alone can do, but that is not now an important capability because individual differences among actual patients correspond to wide ranges of parameter values If we count all the possibly variable parameters, we find that the two channel model with addition plus multiplication at the critical node has about 26, which is greater than the number of facts we have against which to check the behavior of the model From one point of view, that is a disastrous situation From another, one sees that most of the 26 parameters need never be varied and that the variations that are made are constrained by predetermined patterns, but those observations do not wholly overcome the objection that there are too many degrees of freedom"

Is such a model, then, worth while? Does the fact that characteristics of its behavior parallel characteristics of actual audio analgesia give it any value or significance?

In approaching that question, it may be helpful to review the correspondence between model and actual characteristics Of the twenty characteristics we listed, the behavior of the model directly displays the first twelve Implicit in the simple two channel version of the model are places for three more of the characteristics (Nos 13, 14, and 15) Increasing the number of channels would accommodate four more (Nos 16, 17, 18, and 19) An extension would take care of the remaining characteristics (No 20)

Some of the correspondences are obvious Others require interpretive notes

7 Effectiveness of suppression increases with relaxation decreases with tension In the model, relaxation tension is identified with the feedback signals, which can be monitored individually In versions of the model involving multiplication at *the critical node, the gain of* the pain channel depends upon the level of self feedback That level, in turn, depends upon the level of cross feedback from the auditory channel

8 The immediate suppressive effect (which corresponds to the effect that can be observed in a psychophysical context) is less marked than the effect that develops gradually

12 When the pain process and the feedback signals are at low levels, the gain of the pain system is low, and the suppressive influence of the sound has less to overcome

13 If we identify sleep with extremely low levels of tension

(Jacobson, 1938), and if we focus attention on the pain channel, we see that, in a few instances during the stimulation runs, the audio procedure induced sleep. That, of course, is an oversimplification, but it corresponds well with experience in the dental office, and it may go even further. Preliminary observations indicate that infants may be put to sleep by noise of the type used in the audio procedure.

14. Varying the parameters changes the amount of sound required to suppress a given amount of pain. It seems reasonable to suppose that there are large individual differences among people in respect of the neural parameters that correspond to the simulation network parameters.

15. The dentist or experimenter enters the picture only through his manipulation of stimulus variables and of such parameters as relaxation tension. In the actual, clinical situation, that is an oversimplification, of course. Nevertheless, the fact that approximately the same degree of success was achieved by the several dentists, all of whom were aware of the importance of relaxing their patients, is just what would be expected on the basis of the model, and not at all what would be expected if subtle suggestion, or even strong suggestion bordering on hypnosis, were essentially involved.

16–17. In a version of the model with many channels, several channels could be identified as auditory and several others as pain channels. To achieve effective suppression, with such a system, it would be necessary to stimulate many or all of the auditory channels. The advantage claimed by random noise because of its continuous coverage of the frequency scale would then be reflected by the behavior of the model. The advantage inherent in temporal continuity is, of course, reflected by the behavior of even the two-channel model.

18. In a multichannel model, the parameters would vary among the several pain subchannels. Suppression should then change the quality of experienced pain if it did not abolish the pain entirely.

19. In a multichannel model in which parameters varied among the channels, one sense modality would be likely to have an advantage against one pain subchannel, another sense modality against another pain subchannel. That would yield a parallel to the behavior observed with acoustic and photic stimulation.

20. To handle distraction of attention, it seems desirable to introduce a mechanism that will provide an analog of selective interest. It would be best to work with a multichannel model. The responses $r_i$ would then constitute a pattern of nondegenerate dimensionality. Networks could be arranged to provide positive feedback in response to certain patterns, negative feedback in response to others. Such a

system would have a crude analog of attention, and its "attention" would be distractible. We may return, now, to the question of the value of such a model as the one we have been discussing

The main value, it seems to me, stems from the role of the model as an organizer The model pulls a variety of facts together into a compact diagram, and it interrelates them, one to another The model consolidates the experience thus far obtained and makes it easy to go on to extensions and ramifications without losing one's grasp on the things one has already dealt with

A second value that is important in the context of audio analgesia stems from the fact that, although the model displays rather subtle and complex behavior, it is mechanistic That might not be important in a reductionist, laboratory research context, but it is important in the clinical context The model is useful, for example, in providing a nonmentalistic rationale for the part of the procedure intended to facilitate relaxation The model even offers some help in clarifying the question of the role of suggestion it is often suggested that audio analgesia is a form of hypnosis Hypnosis and audio analgesia share the involvement of relaxation and the suppression of pain without the aid of chemical agents However, audio analgesia involves no special relation between patient and dentist, and it appears to be effective for a larger percentage of patients The model serves to turn the question of the relation between audio analgesia and hypnosis from semantics to experimentation One begins to see how the model might be extended to make a place for suggestion and to yield behavior similar to some that is observed under hypnosis One begins to ask not "Is audio analgesia hypnosis?" but "What specifiable processes underlie analgesia, and what specifiable processes underlie hypnosis?"

That takes us immediately to the third hoped for value of the model that it will be useful in formulating experiments and in leading to new observations As mentioned earlier, the model suggests that we look at intersensory effects in general and try to relate to the model the many published results of that field That will be a difficult and probably frustrating task More specifically, the model suggests an experiment to determine the effect of pain on loudness It makes connection with ongoing experiments on effects of sound on sleep and in inducing sleep And, finally, the model demands quantitative data on audio analgesia It makes it clear why experiments carried out in a traditional psychophysical context are unlikely to lead to interesting results In doing so, it may possibly introduce new

variables into psychophysics It seems likely, for example, that the subject's state of tension relaxation may have a significant effect upon subjective magnitudes such as loudness, though perhaps not upon sensitivity to weak signals

There is another side of the question of value, however, and it disturbs me deeply My primary impression of the Symposium was that many oeurophysiologists are so engrossed in their substantive, purely neurophysiological work, and that it is reinforcing them so strongly through advances in uoderstanding of the nervous system, that they do not have time for models There is no way of escaping the cost. Even to set up and exercise such a simple model as the one described here required dozens of hours on the digital computer and several on the analog computer. It is not wholly clear to me that the time would not have been better spent with electrodes in a brain or even earphooes oo ears

My ingrained predispositions toward the realm of models and toward the effort to correlate psychological and physiological data were giveo a sudden shock excitation by a recent letter from Vernon Mountcastle (1959), whose superb presentation at the Symposium greatly clarified my impressions of the reticular formation and the posterior group nuclei, where networks of the kind postulated here may be presumed to lie Mountcastle has found cells, both in the posterior group nuclei and in the cerebral cortex, which respood to nociceptive stimulation and whose responses are suppressed by acoustic stimulation His finding raises the question, whether models can lead to experiments as fast as experiments can lead to models

### Summary

"Audio analgesia" is acoustically induced suppression of pain The phenomenon is genuine but complex and not yet well understood Most of our knowledge about it comes from clinical (especially dental) experience

The present aim is to clarify understanding of audio analgesia by bringing the established characteristics of the phenomenon into relation with one another, and with a few basic psychophysiological ideas, through the agency of a mathematical (or computer) model The model is a very simple one It involves two channels ("hearing" and "pain"), each with positive and negative feedback paths to itself and to the other channel. The dynamic behavior of the model is determined by amplification, biasing, and smoothing parameters associated

with the feedback paths With values of those parameters that are reasonable on a priori grounds, the behavior of the model reflects many of the characteristics of audio analgesia

### Acknowledgment

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perhaps be talking in terms of "envelopes of contraction and relaxation," or some such, we find ourselves saying, "The animal obtained food," or "The subject made a judgment" We tend to classify responses in relation to social significance. Even the statement, 'The rat pressed the bar," implies a little teleology.

The broadest relations available for study and analysis, then, are those between "things" in the world and the complex behavioral sequences they ultimately evoke—what perhaps had best be subsumed under the term, "conduct." This set of relations between objects and conduct defines the domain of behavior theory. It also sets the stage for the first approach to any new communication problem, for when, now, we ask about the potentialities of a little-used sense channel for mediating messages, the broad relation between things and conduct has to be faced

Two radically opposed approaches may be made to the assessment of cutaneous communication possibilities. If a person is interested in the "things" that go into conventional communication systems and in trying to utilize them in novel ways, he may ask, for example, what the skin's capacity is for feeling the disturbances present in a telephone receiver or other electromechanical transducer, and interpreting them This, in fact, is what was asked years ago by those who got interested in "hearing through the skin" programs Their approach was reasonable, given as a starting point the considerations that the skin is quite capable of apprehending mechanical vibrations and that the world contains vast quantities of hardware capable of transducing speech and music into mechanical vibrations of a power level that can be felt by the skin The argument was an evolutionary one—the eardrum, which does so well at picking up and transmitting the fine dance of the air molecules present in speech, is a descendant of a cruder but not dissimilar tissue also capable of behaving with some efficiency in acoustic systems Why not simply train the skin to do substantially what the tympanic membrane does? There were many patient experiments, and enough came out of them to encourage persistent effort Human speech, suitably amplified, was applied to the fingers After a sequence of 28 half-hour training periods, in one experiment, the feeler could learn to judge, with about 75 per-cent accuracy, which one of 10 short sentences had been delivered to the skin After some 30 hours of practice, single words, presented without context, could be recognized about half the time However, even these poor levels of performance deteriorated if the talker changed his rate of presentation or if another person sat in for him The efforts at getting the skin to encompass a language not natural to it eventually

petered out, the approach by way of adapting existing hardware had, for all practical purposes, failed

If one attack is to force a receptor system to perform in an unnatural way by trying to adjust it to the world's hardware, the other involves asking how the world and the things in it might be modified to get the most out of the senses What discriminations are possible for the skin? What is the stuff out of which a cutaneous language has to be built if it is to be optimally utilizable by the skin? Having ascertained what sensory dimensions there are, one is in a position to catalogue the possible discriminations relative and absolute, that might be made along such continua This should yield building blocks, collocations of stimulus properties, for coding One would, indeed, be in possession of the stuff out of which all possible cutaneous communication systems could be constructed, provided only that the dimensional analysis were to be exhaustive and systematic Then it would depend mainly on what had to be communicated—whether the "message" was a warning, directional or rate information, a more sophisticated and elaborate formal 'language," or whatnot—what stimulus arrays were selected out for coding and use

There are but a few stimulus dimensions of the first order available They are easily listed locus, intensity, duration, and frequency, if one begins with repetitive mechanical impacts that is, vibration This is not the only possibility—the skin responds to thermal, chemical, and electrical stimuli as well—but mechanical vibration is the most promising one if continuous signaling is contemplated There are also some derived dimensions, and we shall come to them later What of the first order ones? This is not the place to review all the psychophysical data. They are the joint products of a succession of workers in the Virginia laboratory, and most of them have been published (Geldard, 1957) But we must see where we stand

## First-Order Dimensions

*Locus* has never been systematically investigated, though a good deal is known about it through the studies of Spector and Howell (cf Geldard 1957) The question of how many places on the skin can be utilized is not settled by extrapolation of the results of two point esthesiometer measurements Unlike static pressure, mechanical vibration applied to the skin does not stay within bounds" unless special steps are taken to prevent its spread (Bekesy, 1959) This means that the two point limen for vibration is many times greater

than the static one for a given region Howell found that seven vibrators could be spaced on the ventral rib cage with 100-per cent identifiability of locus, under his conditions This is probably about the limit for a practical cutaneous communication system The chest accommodates five conveniently, and it is tempting—until one finds that it will not work—to consider the combinations of vibrators (31 signals for 5 contactors) that might be coded The difficulty is that two or more simultaneously acting vibrators feel no different from one, once the static pressure of each has adapted out, and provided the vibratory pattern is set up in all of them with the same onset. A split second temporal differential is all that is needed to restore two local impressions, but this leads to the further complication that such a manipulation also provides the essential conditions for synthetic movement, tactual "phi" This, in turn, could be coded, of course, and we shall encounter it again later as belonging in the family of "derived" phenomena.

The failure to explore the entire body for locus as a codable cue is not the result of neglect, nor yet of lack of interest in the outcome In this electronic age so many things have to await technological advance We simply have not had a transducer with the right properties to make the experiment feasible When Dr Howell had an array of eight vibrators on his subject's chest, he was literally trapped in a forest of concrete rooted supports, flexible goosenecks, and long, flat springs that were necessary, with the vibrators then in use, to ensure independence of vibratory generation and to preserve a uniform static background pressure. It is, therefore, a considerable satisfaction to report at this time a technological "breakthrough" of recent weeks whereby my colleague, Dr R C Bice, has succeeded in modifying radically a transducer of the hearing aid variety to provide strong, low frequency vibrations which are not readily damped by the skin He has also found an ingenious way of utilizing fabric fasteners to couple the vibrator firmly to any chosen site of stimulation. The instruments are sufficiently small and light and their electrical properties are such that they yield high powers without undue beating. For the first time the systematic exploration of the dimension of locus seems to be in sight.

What of *intensity*? There have to be some limits Each part of the integument has its own absolute threshold, and each part has its susceptibility to both discomfort and damage by the trip-hammer action of powerful vibrators In the region of the chest, a useful range of stimulus amplitudes is bracketed by the values, 50 to 400 microns, the former because it is safely above the 100 per-cent abso-

lute threshold, the latter because it falls well below the threshold of discomfort Between these limits the average observer can, under laboratory conditions and with the use of a careful psychophysical procedure, detect about 15 intensitive steps On an absolute recognition basis, unless one were to select subjects or train them, it would be unsafe to include more than three steps, widely spaced over this range The intensitive dimension is, in fact, the least exploitable of all the first order dimensions An analysis of errors in a communication system that codes locus, intensity, and duration shows nearly all mistakes to be made along the dimension of intensity There appear to be two chief reasons for this (1) a fixed amplitude applied to different loci varies considerably in its "feel," owing perhaps to accidents of local innervation, perhaps to reinforcing or damping variations in underlying tissue, (2) it is not easy, in the face of breathing motions and those coming from circulatory events, to maintain a strictly invariant relation between a mechanical vibrator and the skin surface on which it rests

*Duration* of a continuous vibratory "package" is judged with some precision over the entire useful range The range must, of course, be selected on extraneous considerations In our experiments we have chosen not to deal with any durations under 0 1 second, this on the ground that a "buzz" much shorter than this is likely to be mistaken for a "nudge" or a "poke" At the other end of the scale, we have set 2 0 sec as a limit beyond which we are unlikely to wish to code signals, a communication system employing units lasting more than 2 sec is certainly a ponderous one Between 0 1 sec and 2.0 sec, then, there is a durational continuum within which the average observer can make about 25 distinctions, the steps being of the order of 0 05 sec at the low end and 0 15 sec at the high end of the range This is again the relatively precise $\Delta t$ of the psychophysical experiment Absolute identifications with 100-per-cent accuracy yield four or five considerably more widely dispersed levels, and, if neither selection of subjects nor training of them is intended, it is safer to use only three.

It is clear from the foregoing that three sets of building blocks of cutaneous communication systems are in our possession—a limited number of absolutely discriminable steps of locus, intensity, and duration There is, of course, a fourth primary dimension. This is *frequency* The story of frequency discrimination in the vibratory realm is not a simple one There is a history, and also some recent experiments have had interesting outcomes. The history we may summarize by saying that failure to control for differences in subjec-

two intensity, when frequencies were being compared, and for contaminating transients at the onset and offset of the stimulus envelope has invalidated all measures prior to those recently obtained by Genevieve Goff in our laboratory (Goff, 1959) She overcame these defects by first assembling a band of equal loudness stimuli, differing

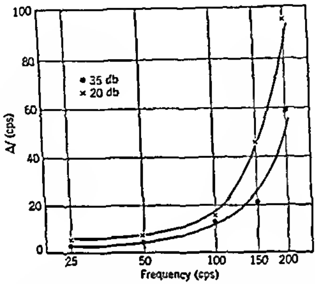


Fig 1 Differential frequency discrimination of mechanical vibration applied to the finger tip (Goff, 1959) The curves are for a single subject.

in frequency, and then measuring $\Delta f$ systematically throughout the obtainable frequency range Her basic results are shown in Fig 1

It is clear that, at very low frequencies, judgments of vibratory "rate" are quite good, but it is equally clear that discriminability fades rapidly as the frequency scale is ascended. In the region best for speech sounds the skin does very badly indeed, and this finally explains why the "hearing through the skin" programs, alluded to earlier, yielded such disappointing results A direct comparison between the skin and the ear is made possible in Fig 2, the auditory data are the classical curves obtained in the Bell Telephone Laboratory (Shower and Biddulph, 1931) at a roughly comparable intensity level.

There is one additional difficulty where vibratory frequency is concerned, were it not for this, it might conceivably be possible to transpose audible frequencies downward into the tactile range The difficulty is this—the correspondence between vibratory frequency and perceived "pitch" is a tenuous and uncertain one Vibratory pitch proves to be a joint function of both frequency and amplitude

To be sure, this is also the case, for much of the audible range at least, in hearing as well, but intensity is only a very minor determinant of auditory pitch, making pure tones louder or softer can move pitch about only a little Frequency is very nearly in absolute control In the cutaneous sphere things are different Increase the amplitude of a moderately loud 40 cycle sinusoidal vibration applied to the

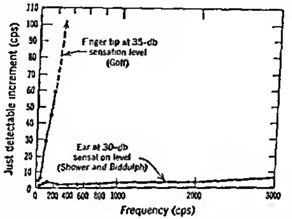


Fig 2 Discriminability of vibratory frequency ($\Delta f$) compared with the auditory pitch discrimination data of Shower and Biddulph, 1931 (after Goff, 1959)

finger tip, and it undergoes a marked downward shift in pitch De crease the amplitude, and its rate goes up perceptibly Békésy has recorded shifts of the order of three octaves (Békésy, 1959) It is obvious that frequency would have to be handled gingerly in a communication system, especially if intensity were simultaneously manipu lated as a variable

### A Workable Vibratory System

In our initial efforts to form a system of vibratory signals capable of being coded, only the three obviously useful dimensions of locus, intensity, and duration were employed The code shown in Fig 3 was devised and applied successfully by Howell, so successfully that a subject who had invested a total of 30 hours in learning the alphabet of the "vibratese" language could, after a further training period of only 35 hours, receive sentences with 90-per-cent accuracy when transmitted at the rate of 38 five letter words per minute (Howell, 1956)

This performance in no wise represents the optimal attainable

Using the same rules as those of international Morse code with respect to interword and intraword spacing (0 1 sec and 0 05 sec, respectively), the system requires only 0 79 sec to transmit the "average" five letter English word This means that the ceiling transmission rate is 67 words per minute, a speed well over three

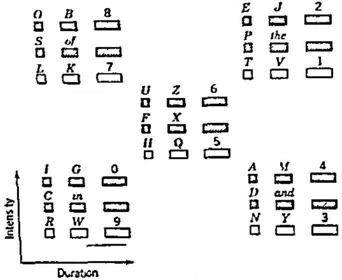


Fig 3. Code of the "vibratese" language (Howell, 1956)

times that of proficient Morse To approach this rate, however, there would be required an extensive and somewhat elaborate engineering job to devise an automatic coder—perhaps of the tape variety—that would initiate signals faster than our present homemade machine, a manually operated typewriter that triggers "flip-flop" circuits (for time) and a bank of potentiometers (for intensity). The closing of the gap between 38 and 67 words per minute we leave to those interested in establishing world's records

#### Future Potentialities

Meanwhile what other building blocks are available? We have considered only the first-order dimensions of the vibratory stimulus There are some derived dimensions, a few of which have already received some attention. It would be helpful to have additional codable cues, if only to be in a position to add redundant elements Much has been written about purifying and simplifying languages by reduction of redundancy Where intelligibility is less than optimal

there is much to be said for making the language more, rather than less, redundant (Miller, 1951, p 103), and the vibratese language would doubtless benefit from this kind of doctoring

What are the candidates here? Intensity variations as a function of time present one set of possibilities A signal may be imposed on the skin quite abruptly or more gradually, just as in music one may have variations in "attack, "hitting" a tone or 'sliding into" it Sys

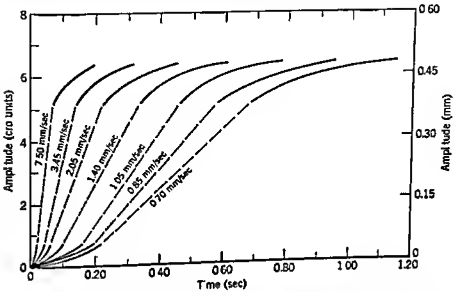


Fig 4 Variable rates of rise from zero to a vibratory amplitude of 480 μ The seven curves have been drawn to mark off six successive jnd steps (Howell, 1958)

tematic manipulation of this variable has been carried out by Howell Figure 4 serves to describe both how the envelope shapes were made to vary and how discriminability of rate of onset changed with decreasing rate of attack. For a growth of amplitude from zero to 480 microns—the largest that it was practicable to work with—and for rise times that ranged from the shortest that the system could produce without transients to the longest that might serve for signaling purposes, there prove to be six discriminable steps As with all other similar functions, these come from the conventions of psychophysics Absolute identifications are, of course, not spaced this closely Indeed, if 100-per-cent recognizability of "attack rate" is demanded, over this range of onset slopes there are but two the "magical number" proves to be 7 minus 5! There are presumably another two steps associated with offsets

A second possibility, in the realm of derived dimensions, is wave

form This has not been investigated yet, though it is clear that wave form variations should be discriminable if the basic frequency is low enough Still other moment-to moment variations should be detectable Perhaps it would be possible to introduce variations within signal envelopes other than those of onset and offset, a gradually increasing or decreasing frequency, say This is an unexplored field.

Another patterning of stimuli involves space as well as time As in vision, the successive stimulation of two separated receptive areas, provided the temporal relations are right, leads to perceived movement. Unlike vision, the critical time relation for tactual "phi" is the absolute interval between the beginnings of the two successive exposures, not the duration of the silent interval between them Indeed, there need be no silent interval at all The exposures may overlap and still yield good movement if the onsets are properly spaced. Cutaneous phi has been surveyed, not so much with a view to coding it and incorporating it into a communication system, as to studying its essential conditions as a phenomenon, but clearly it offers some possibilities

It is doubtful whether vibratory phi should be coded into any language of the type described above Indeed, in any rapid succession of signals applied to spatially discrete loci, the crucial conditions for synthetic movement are already given Movement has to bo overlooked, not apprehended in this situation, of course On the other hand, the phenomenon of cutaneous movement is an extraordinarily powerful one, it really commands attention Place a ring of vibrators around the body, for example, three across the front and three across the back of the thorax, energize them successively with a 0 1 sec temporal separation, and the observer feels a vivid "swirling" motion, entirely novel in his experience, because he seems to be at the center of it! This effect is a completely prepossessing one and, accordingly, it is ideal for coding in a different fashion, say, as a warning signal to be infrequently used but capable of highly significant coding It would do valiant service attached to a "panic button"

This raises the important question of the ultimate place of the cuta neous channels in the total communication picture Coding to letters and numerals is really a quite pedestrian way of getting meanings into tactile patterns There are, to be sure, obvious ways of making such a system "fly" at a faster rate One way would be to code the vibratory signals to phonemes We have not attempted it because of the prodigious investment entailed in learning the phonemes them selves, but it ought to be tried It is also possible that there may

come out of hiding an entirely novel cutaneous shorthand, one capitalizing on distinctively tactile properties Serious study of basic cutaneous perceptual phenomena, an area dignified by the devotion of not more than a dozen first rate minds in the whole of recorded history, might turn up such a linguistic development

## Vibratory Tracking

The possibilities of cutaneous communication are by no means confined to conventional language, of course Other kinds of information may be imparted tactilely Rates, amounts, directions—anything falling on unidimensional or bidimensional continua could presumably be represented to the skin by means of suitably patterned mechanical impacts or sequences of them One of these possibilities has already been exploited in our experiments Vibratory tracking by compensatory pursuit has been carried out by lining up three vibrators across the chest and letting them be successively energized to give the impression of continuous movement in one direction or the other (through utilization of "phi") The "arrowhead" was always "pointed" toward the target, and the vibratory sequences were temporally spaced to indicate degrees of urgency in getting back "on target" The subjects manipulated a steering wheel and attempted to eliminate all cutaneous signals by promptly neutralizing all off target indications

Ten subjects performed in response to these tactile signals Ten others were presented the visual analogue, with lights substituted directly for the vibrators Both groups learned rapidly, and the vibratory performance was in no wise inferior to the visual. Comparative learning curves are shown in Fig 5 Although the visual conditions are not optimal for this sense—the target was "traveling" at the rate of only 3 5 degrees per second, and the eye of course, can handle speeds many times as great—the tracking task imposed on the subjects was one that would keep all but the speediest vehicles comfortably on course, and the skin was handling the assignment fully as well as the eye

Subsequently, this experiment underwent simplification Synthetic movement was taken out of the display, the three vibrators were reduced to two, and even the "urgency" feature was eliminated Now there occurred only a simple "nudge," a brief burst of 60-cycle vibration to indicate direction off the target to the right or left. Performance showed no significant degeneration with this removal of

redundancy in the signal Very little is needed to give directional information that is adequate to fairly complex performance

Currently there is being tested a bidimensional vibratory display designed to give both "right left" and "up down" deviations from the target (glide path? trajectory?), and there is every indication that the system will do what is expected of it The value for situations in which vision and hearing are pre empted, for one reason or another, is obvious

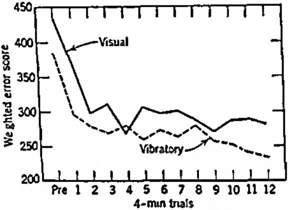


Fig 5 Comparison of visual and vibratory tracking performances The error scores were weighted for distance off target (Bice, 1953)

Another whole domain of possibilities opens up when we consider that only one form of energy, the mechanical, has thus far entered our calculations Not much is to be hoped for from the chemical and thermal forms of stimulation They are both too ponderous in their operation to be of much use in communication, at best they could provide only the analogues of smoke signals But there is the whole important realm of electrical stimulation The skin responds with lively patterns to both direct and alternating current Indeed the heart of the problem is that the patterns are, in general, somewhat too lively for comfort We have devoted several years of intensive effort to finding the conditions of electrical stimulation that will yield codable vibratory patterns bereft of pain, and that can be reproduced on demand The problem has turned out to be a slippery one Electricity is the great "nonadequate" stimulus, it triggers everything, as physiologists well know However, the important stimulus parameters are few in number, and my colleague, Dr John F Hahn, has been able to isolate the really significant one in skin stimulation (Hahn, 1958) As Fig 6 taken from his work shows, where square

waves are employed and are systematically varied in frequency and duration, thus obviating any influence of the change in rate of current increase such as occurs with alternating current of variable frequency, it turns out that absolute threshold is related to duration only. This

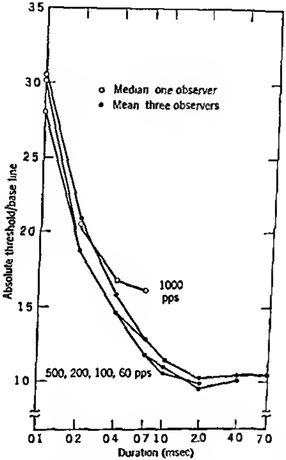


Fig. 6. Strength duration curves at several rates of repetition of direct square-wave stimulation of the skin. Absolute threshold/base line is the ratio of absolute threshold to the mean of thresholds with pulse durations of 2 0 msec or longer, pps is pulses per second (Hahn, 1958).

fundamental discovery permits us to narrow our search for the basic medium of reception in electrical sensitivity of the skin. The great stumbling block, thus far, is the omnipresent pain. Although under some reproducible conditions pain tends to adapt out in continuous signaling, leaving behind a not too unpleasant tingle, it is doubtless asking too much, in practical communication situations, to expect that even transient discomfort from a transducer will be tolerated.

## Summary

A really comprehensive approach to communication problems entails not only the domains implied by the terms, "stimulus," "physiological changes," and "response," and the three sets of relationships into which they enter, but the much more remotely related terms, "physical objects" at the beginning of the series, and "conduct" at the end of it. The position one takes on these relations has much to do with how questions concerning communication are to be asked.

There are reviewed the currently available facts concerning cutaneous sensibilities, insofar as they have bearing on the communication problem. The possible elements of a cutaneous language are identified as those collocations of stimulus properties that are recognizable in the absolute. The first-order dimensions of mechanical vibration (locus, intensity, duration, frequency) provide the major possibilities, though interactions between frequency and intensity are such as to render one or the other of these difficult of utilization. A few steps of locus, intensity, and duration provide enough codable signals to make rapid and accurate communication possible.

In addition to the primary dimensions, there are some secondary or derived ones. Intensity variations as a function of time ("attack") constitute one such possibility. A second dimension is the derivative of frequency, wave form. A third involves both spatial and temporal variations, synthetic cutaneous movement. The first and third have already received some attention, the second has not been much investigated as yet. Movement (cutaneous "phi") is especially useful in unusual warning situations because of its vividness. It has also served as an intensifier of signals in tracking situations.

A second contender for prominence in future cutaneous communication systems is electrical stimulation. The possible stimulus parameters are few in number, and recent work has shown pulse duration to be the important one in sensitivity measurements. Direct electrical stimulation of the skin minimizes the transducer problem and is ultimately to be preferred over mechanical systems if the ubiquitous problem of pain can be circumvented.

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# 5

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# Selected Developments in Psychophysics, with Implications for Sensory Organization

The purpose of this chapter is to outline some selected recent developments in psychophysics that may be relevant to problems of sensory organization In this discussion it is assumed that psychophysics is concerned primarily with "terminal" activities, in that specified sensory inputs are related to specified behavioral outputs, without direct observation of the dazzling complexity of intermediate neural events Psychophysical data are thus necessary, but not sufficient, for a complete model of sensory organization From this point of view, psychophysics will be considered to suggest crude alternative models, or broad strategies of action, for approaches to the sensory organization of the human observer, rather than crucial details All references to the nervous system in the chapter refer to a conceptual nervous system that serves between the terminal activities of stimulus and response.

## Psychophysics and Information Measurement

The outstanding impact of information theory—more accurately, of information measurement—upon psychophysics has been the specification of the stimulus (Quastler, 1956) Instead of the specification of a particular energy configuration, information measurement has called for the specification of the entire *ensemble* of possible events to which the organism might be exposed in a particular situation Although minor contextual effects have long been known to psychophysics, the concept of the ensemble of possible stimuli far transcends second-order effects In the light of information measurement, the entire ensemble of events becomes, in effect, a superordinate stimulus

With the same impetus, the psychophysical behavior of interest becomes the stimulus response *confusion matrix* which relates each of the possible responses to each of the possible stimuli (Miller and Nicely, 1955) The stimulus response confusion matrix in turn is crucial in testing alternative models of sensory organization These models consider the representational mapping of stimulus objects on the relevant portion of the conceptual nervous system This relevant portion will be termed the *discrimination space* In particular, two extreme alternative models will be further considered in detail

### The fixed-map model

The fixed map model of sensory organization implies a complete lack of interaction among the alternative stimulus objects of the ensemble (Luce, 1959) The model implies that the mapping of any specific stimulus object onto the conceptual discrimination space is invariant with the other members of the stimulus ensemble That is to say, corresponding to each stimulus object there is a location in the discrimination space, and the location associated with a particular stimulus object does not depend upon the other members of the ensemble

In terms of psychophysical results, the model suggests that any stimulus of the ensemble is effective only insofar as the stimulus contributes responses to the total pool of responses Removal of the stimulus and redistribution of its corresponding responses within the remaining stimulus response confusion matrix leave the ratio among specific stimulus-response confusions unchanged Hence, the predictive instrument for the fixed map model has been termed the constant ratio rule (Clarke, 1957) It should be noted that the model makes no assumption of the distribution, or of the scalar properties, of the objects of the stimulus ensemble

### Rubber-band model

An alternative model of sensory organization assumes a high degree of interaction among the members of the stimulus ensemble It assumes a variable mapping of the stimulus ensemble onto the appropriate discrimination space, depending upon the available range of stimulus objects in the ensemble The discriminative *density*, in turn, is inversely proportional to the range The change in density with range may be illustrated by marking off equal distances on a rubber band, and then counting the number of marks as the band is stretched and contracted, with reference to a fixed length. From this illustration, the model gets its name the rubber band model of sensory

organization (McGill, 1958) In terms of the model, any specific pair of items may be highly discriminable if the entire range under presentation is narrow, but poorly discriminated if the entire range is wide

The rubber band model, however, does not yield exact quantitative prediction unless we assume that the discrimination space is always stretched to accommodate the entire range of the stimulus ensemble This assumption is unreasonable, for it would result in the prediction that the discriminability between any two stimuli, of an ensemble of only two stimuli, would be independent of the differences between the stimuli This is certainly not the case Further, whereas the rubber band model may reasonably be applied to stimulus ensembles that may be arranged along a single physical continuum, it is not evident how the rubber band model would accommodate stimulus ensembles that vary along several physical continua. These points suggest that predictions based on the rubber band model might be successful only for stimulus ensembles that vary with respect to a single physical variable, or a small number of variables

### *Confusion-matrix results*

Several empirical studies have now shown that, for stimulus ensembles of a high order of physical complexity (for example, words presented in noise, letters presented in a brief flash), the constant ratio rule is an excellent predictive instrument, even for relatively small confusion matrices (Clarke, 1957, Clarke and Anderson, 1957) Said otherwise, with these stimulus ensembles the fixed map model appears to lead to precise prediction of psychophysical data.

Stimulus ensembles that vary with respect to only one variable do not yield clear evidence Preliminary data (Clarke, 1959) suggest that large deviations from the constant ratio rule (in the direction predicted by the rubber band model) are observed for stimulus ensembles in which only a single variable is manipulated However, these deviations are observed only with small confusion matrices and only when the stimulus objects of the ensemble are highly discriminable For larger confusion matrices, or for small confusion matrices in which the stimulus objects of the ensemble are highly confusable the constant ratio rule is an excellent predictor of the psychophysical findings, even for stimulus ensembles that vary with respect to a single variable (Hodge and Pollack, in preparation)

Thus the concept of the stimulus ensemble, derived from information measurement, with the associated stimulus response *confusion matrix* permits examination of alternative models of sensory organization The weight of evidence favors a model that assumes that stimu

background On the other 50 per cent, there is no additional flash The detection system consists of a photocell sensor and a response threshold detector, such that if the output of the photocell sensor reaches a critical response level, the system responds "flash", and, if the sensor fails to reach the critical response level, the system responds "no flash." Let us assume that, on successive occasions, the response threshold detector may be set to different critical response levels

If the critical response level of the threshold detector is set extremely low, the photocell system "sees" nearly all the flashes, that is, it registers the presence of the flash upon nearly all the trials in which the flash has been presented In the language of signal detection, a high "hit" probability has been achieved The price that must be paid for setting the critical response level low is that the photocell system may register often the presence of a flash on trials in which the flash was not presented. In the language of signal detection, a high "false alarm" probability would be obtained Thus, when the critical response level is low, a high hit probability is associated with a high false alarm rate

Similarly, if the critical response level of the threshold detector is set high, the system may fail to report many of the flashes on trials in which the flash was, indeed, presented And, in the same manner, the system would rarely register the presence of a flash on trials in which the flash was not presented. That is, when the critical response level is high, a low hit probability is associated with a low false-alarm rate

Note that, with the same photocell sensor, a wide range of hit probabilities, with an associated wide range of false alarm probabilities, may be obtained simply by varying the critical response level of the threshold response detector operating upon the information furnished by a sensor of the same photocell system Should we now conclude that under these conditions the photocell sensor is changing in its sensitivity or discrimination of the flash above the background illumination? No, it is not reasonable to infer changes in the behavior of the photocell sensor, for its characteristics are determined by its own construction relative to the sensing environment under examination. It is rather more reasonable to assume that the discriminability of the photocell sensor is constant and that the operating level of the decision part of the system is changing. This distinction between the *discriminability* of the sensory part of the system and the *operating level* of the decision components of the system, acting upon the sensory information, is crucial.

What has been said for the electronic photocell system can also be said for the human discriminator Under a given set of viewing conditions of observation, a wide range of operating levels may be obtained by varying the instructions to the observer or by varying the relative values and costs of missed detections and false alarms In fact, it is possible to show that, under a specific signal and noise condition, the discriminability of the human observer is invariant over a wide range of operating levels (Egan, Schulman, and Greenberg, 1959, Pollack and Decker, 1958, Tanner and Swets, 1954)

What are the implications of the signal detection approach for sensory organization? The primary implication is that, whereas a *response* threshold detector is reasonable, a *sensory* threshold detector is not tenable The experimental evidence indicates strongly that the sensory information about the environment is preserved in a form such that a continuous range of information is available for subsequent decision making

The negation of the sensory threshold is of course, a radical notion—so radical as to invite immediate suspicion In the comment, "Is There a Quantal Threshold?" (in this volume), Stevens takes an opposite position He points out that, in every experiment carried out within the framework of signal detection, noise has been introduced with the signals to the observers He notes that the introduction of noise is alone sufficient to mask the "sensory neural quantum" (Miller, 1947) Experiments with pure tones (Stevens Morgan, and Volkmann, 1941) may, or may not, yield the sensory quantum Further, it is argued that the forced choice procedure of the signal detection approach places an unnecessary burden on the observer which tends to mask the sensory quantum Much heat can be generated by arguing these points At present, however, it seems more profitable to determine whether we can set up an experimental test between the statistical detection and the sensory quantum approaches The following set of experiments might provide such a test if a number of assumptions can be met

First we recreate the conditions of the initial Stevens, Morgan, and Volkmann experiment, in which the "neural quantum" was observed. We assume that we are successful in obtaining a fortunate selection of observers capable of maintaining an unwavering attention over extended periods of time" so that quantal functions can be obtained We also assume that we can get the listener to make a confidence rating of each of his responses without disturbing the quantal function (For a discussion of the use of confidence ratings see Egan, Schulman, and Greenberg 1959, Pollack and Decker, 1958 ) And,

finally, we assume that we can interpose a small number of "catch trials," in which the signal is not presented, without disturbing the quantal functions of the observer

If the neural model is represented by a discriminative continuum, the listener's confidence ratings should reflect his accuracy of judgment on the critical trials On the other hand, the sensory-quantum approach predicts that the listener's confidence ratings will not reflect any difference, owing to the quantal nature of the changes In this regard, it may be noted, the original article reported that large intensity increments often "sounded louder" than small ones (Stevens, Morgan, and Volkmann, 1941, p 334).

Of course, the experiment cited above may not be feasible As Stevens and others (Miller and Garner, 1944) have noted, any disturbance of the observer often results in the failure to obtain the neural quantum. Adding the confidence response may vitiate the entire experiment. Still the approach may warrant a serious attempt.

The theory of signal detection has another—and potentially more important—implication for sensory organization The theory defines an *ideal observer*. The ideal observer is a performance model that is able to extract all available information from the signal and noise environments (Tanner and Birdsall, 1958) The ideal observer sets an upper limit on the discriminability of the observer under examination—whether human or electronic.

Experiments demonstrate that the human observer performs poorly relative to the ideal observer in the detection of weak signals in noise. Here the ideal observer can use phase information and other classes of information that are not employed effectively by the human observer But the human observer's performance approaches that of the ideal observer for the recognition of large signals, that is to say, at favorable signal to noise ratios (Tanner, 1957) It may be noted that the memory requirements imposed upon the observer for strong signals are substantially less than for weak signals The full implications of these findings for sensory organization are not yet clear There is an undercurrent of excitement that suggests that powerful implications will follow clarification.

And, finally, the author would be remiss if he did not attempt to capture the flavor of the signal-detection approach to present-day psychophysics In this framework, the trained human observer becomes an active goal seeking discriminator with the ability (within limits) to vary characteristics of his sensory equipment and of his decision and operating levels Though this picture is too molar to permit resolution of details of sensory organization, it may be profit-

able to make room for such flexibility in considering the molar properties of the sensory organization of the human observer.

## Summary

Two recent contributions to psychophysics—information theory and signal-detection theory—have been briefly considered insofar as they may point toward molar properties of sensory organization of the active human observer. Psychophysical data, which reflect only stimulus-response correlations of the molar observer, by their very nature cannot be expected to reveal the details of the actual neural substratum of sensory organization.

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# 6

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# Two Ears — but One World

## The Formation of Binaural Gestalten

*I* believe it was Epictetus the Stoic who was reported as saying, "God gave man two ears, but only one mouth, that he might hear twice as much as he speaks"

This wishful thought may be empty, so far as human wisdom is concerned, but it is curiously near truth on the plane of psychophysics For the possession of two ears gives us greatly enhanced powers of aural discrimination we can the better separate a single voice in a buzz of conversation and attend to it, or we can single out a voice from the sounds of traffic, or of the wind, and all the myriad of disturbing noises The brain takes maximum advantage of the slight differences between the signals that reach the two ears—differences in timing, in intensity, and in microstructure—and by processes of inductive inference breaks down the complex of sounds into separate coherent images, *Gestalten*, which becomes projected to form the subjective "spatial world" of sound

The basic fact about any one of these images, say that of a voice, is that it is single, with two ears we hear only one world By what logical processes does the brain examine and analyze the sense data reaching the two ears, so as to achieve this fusion? Understanding of the fusion process seems to be fundamental to an understanding of directional hearing Understanding of the logic of the processes whereby voices in a crowd can be separated is a parallel problem, for we *can* separate voices, and other *Gestalten*, with one ear alone but with reduced effectiveness

In this chapter we shall be concerned only with this basic phenomenon of fusion, discussing it as a psychological problem and its description as a logical (mathematical) problem Physiology will not be mentioned, for we shall not look inside the head at all On the contrary, we shall try to set up a model to describe what "must" be

there. Before you physiologists charge me with arrogant presumption in saying this, I should ask you to remember two things. First, we are not saying what physiological *mechanism* must be there, but only by what logical principles it can be described as carrying out its functions (for example, whether it adds or multiplies or integrates); second, if you disagree with any aspects of our mathematical model, it is up to you to show that the logical operations are *physiologically* impossible. If you succeed, we on our side will retract and re-examine our logic (or, more likely, our premises).

The model of binaural fusion, to which I refer here, has been described elsewhere in complete detail (Sayers and Cherry, 1957). It is largely the result of the extensive experimental and computational work of Sayers while he was a student in my group at Imperial College, London.

### To Fuse, or Not to Fuse?

In order to study fusion, as opposed to directional hearing (Cherry and Sayers, 1956), we eliminate the effects of head turning by fitting the subject with headphones. If the two earphones are driven with identical signals of any kind, the subject hears a single fused image located in the center of his head. If the interaural time difference $T_e$, or the relative intensity $A_L/A_R$, of the left- and right-hand signals is varied, the image appears to move across the head laterally in a line between the two ears. The image does not appear to pass outside the head and has no angular direction, as in real life; it has only lateral position, left to right.

We control the lateralization by varying the interaural time interval $T_e$ only, driving each earphone from a separate reproducing head on a special magnetic tape recorder, running at high speed. The interaural time interval $T_e$ can be set to any value to an accuracy of less than 20 microseconds.

The interval $T_e$ is set to a succession of random values (using a table of random numbers), and the subject is required to guess whether the fused image appears to be to the right or left—a dichotomous judgment, $R$ or $L$. The forms of such lateralization "judgment curves" fall broadly into two classes. (1) If the source is predominantly random, or quasi-random, the form is like that shown in Fig. 1a. When $T_e$ is large (say 1 to 5 milliseconds), the subject answers 100 per cent correctly; when small, he makes errors; when zero, he is (by chance) correct about 50 per cent of the time. (2) If the source is

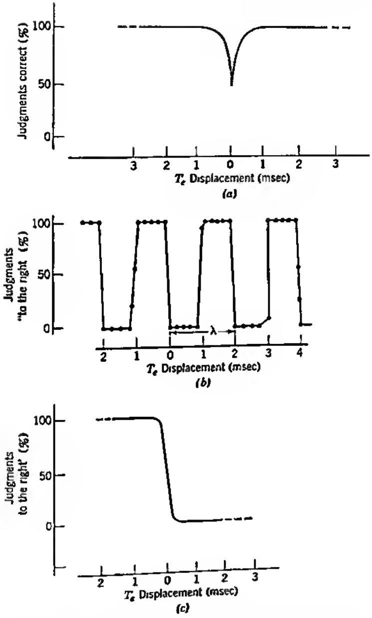



Fig. 1. Fusion judgment curves for random and periodic sources (*a*) lateralization for a white noise source, speech source, or a similar quasi random source, (*b*) lateralization for a periodic 800 cps source, (*c*) replotting of curve (*a*) in terms of percentage of judgments to the right

predominantly periodic, as with pure tones or multiple tones, the curve itself is periodic, as shown in Fig 1*b* for a pure 800-cycle-per-second sine wave These two forms of curve represent extreme tendencies,

real life sources of sound contain both (quasi ) periodic and stochastic components

We shall concentrate first on sources of type 1—for example, speech or noise

This downward dip in Fig 1*a* represents the subject's uncertainty, which has at least two origins (1) since the fused image has a finite subjective size, its central point is uncertain, and (2) the subject is uncertain of his own midplane (intracranial) about which he is making acoustic judgments

The arbitrariness between zero values of $T_e$ on the magnetic tape and the central (intracranial) plane is removed by replotting Fig 1*a* in terms of percentage of right hand judgments, as in Fig 1*c*, thereby skewing the curve This method is adopted hereafter for all forms of "judgment curve" The fact that $T_e = 0$ now is not to be taken as "an applied central image" Note that Fig 1*b* is plotted this way also

So much, briefly, for the case of identical aural stimuli If, however, the left and right signals, $S_L(t)$ and $S_R(t)$, are utterly different (statistically independent), say, two different voices, or different noises, then no fusion takes place (Cherry, 1953) What we are here regarding as a "fusion mechanism" is not triggered This mechanism is then operated, or not operated, as determined by the relation between $S_L(t)$ and $S_R(t)$

It has been our purpose to examine experimentally the nature of this critical relation and to find a model for the analytical processes whereby the brain determines it, as a control for the "fusion mechanism"

Obviously it is far more interesting to see what happens when $S_L(t)$ and $S_R(t)$ are neither identical nor totally unlike, but only *partially* alike In what sense is "alike" to be defined? What does the brain look for in its running analysis?

If we were to confine ourselves to the use of simple determinate signals, like sine waves, clicks, and so forth, we might oversimplify the problem For in real life the aural stimuli, such as human speech, street noises, and so on, are stochastic "Stochastic" means "probabilistic", the brain cannot know in advance exactly what is coming to the ears next, in microscopic detail instant by instant Further than this the two signals $S_l(t)$ and $S_R(t)$ are never *exactly* alike, in detail, in real life They differ not only in timing $T_e$ and average intensity $A_L/A_R$ owing to the spatial directions of sound sources, but in other ways owing to head sound shadows, reflections and reverberations, and random sound contributions from the wind on our faces

Again, in real life, an aural image stays fused and does not hop about as the two aural signals fluctuate It must be average statistical, invariant properties that control this "fusion mechanism, and several different storages may be used, for different averaging times

Mathematically speaking the measures that assess the average (statistical) degree of dependence, or independence, of stochastic sources are the *correlation functions* There are different forms of such measures but certain other real life conditions under which the brain must operate, narrow down the possibilities Such functions have found a considerable place in models of other aural phenomena, notably in the work of Licklider (1951 1956), especially in connection with pitch perception and spatial separation but not, so far as we can find, in models of binaural fusion prior to our 1956 paper (Cherry and Sayers, 1956) We shall be returning to such theoretical aspects in a later section

## Experimental Control of the Statistical Independence of the Two-Ear Signals

Before theorizing further, let us refer to some experiments Figure 2 shows the same binaural stimulus arrangement as resulted in the curves of Fig 1, except that now band limited white noise is added to the signal at one ear only The magnitude of this noise $N(t)$ in relation to that of $S(t)$ controls the statistical independence of the two ear stimuli to any degree we wish

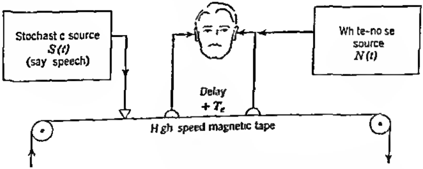



Fig 2 Control of the statistical dependence between the two-ear stimuli.

Figure 3*a* shows a typical judgment curve (percentage of left judgments) as $T_e$ is set to successive random values when $S(t)$ is male speech. This curve differs from that of Fig 1 in two ways (1) Dips appear, showing less certainty of left lateralization of the image at

certain values of time $T_e$. Fusion is now only *partial* over various regions of interaural delay $T_e$. (2) A total left-right dissymmetry shows *total fusion* when the pure speech signal leads in time but *partial*

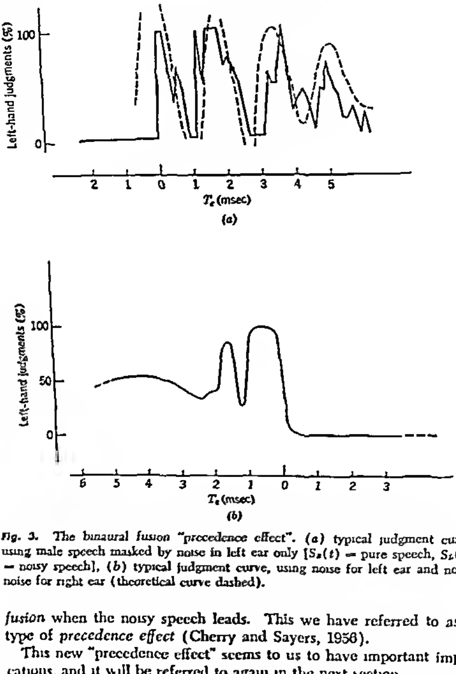



Fig. 3. The binaural fusion "precedence effect". (*a*) typical judgment curve using male speech masked by noise in left ear only [$S_R(t)$ = pure speech, $S_L(t)$ = noisy speech], (*b*) typical judgment curve, using noise for left ear and noisy noise for right ear (theoretical curve dashed).

*fusion* when the noisy speech leads. This we have referred to as a type of *precedence effect* (Cherry and Sayers, 1956).

This new "precedence effect" seems to us to have important implications, and it will be referred to again in the next section.

My colleague Dr Sayers has made extensive measurements of such

binaural "judgment curves," each the result of one to two thousand separate right left judgments with randomly set time delays Partly from such curves the nature of the analysis performed by the brain (in the "fusion mechanism") has been exposed This analysis is required, in part, to determine the degree of statistical independence of the signals that arrive at each ear in real life, since this assessed degree of independence is a measure of the likelihood that these two signals come from a single external source of sound If this likelihood is higher than some threshold (not necessarily constant), fusion is enforced, if lower, separate images are set up at each side of the head

If the logic of such argument is accepted, we are led to the conclusion that the "fusion mechanism" can be described as carrying out some type of correlation analysis, though there can be many forms of such measures To determine the precise form used by the "fusion mechanism," further experiments were performed using not only stochastic signals like speech and noise but determinate ones such as sinusoids We shall return to these experiments later, in the section on Binaural Fusion of Speech. But first let us return for a moment to the curious "precedence effect," already noted.

### The "Precedence" Assumed by a Pure Sound Source at One Ear over a Noisy or Distorted Source at the Other Ear

There are other "precedence effects" in hearing, but the one referred to earlier and illustrated in Fig 3 has not been reported, so far as we are aware, prior to our 1956 and, in more detail, our 1957 papers (Cherry and Sayers, 1956, Sayers and Cherry, 1957)

The effect was mentioned only in passing in these papers, and the writer would like now to take the opportunity of calling the attention of psychologists and neurophysiologists to it, since there may be important implications

With reference to Fig 3 the effect is this if the "pure" signal $S_R(t)$ (say, speech) is set earlier in time than the noisy signal $S_L(t) + N(t)$, then total fusion takes place, with zero uncertainty concerning its right left localization, over a wide range of signal to noise ratios, provided the delay $T_e$ is greater than some residual amount (about 100 microseconds in practice), but if the noisy signal is earlier in time, fusion is quite varied and uncertain This total dissymmetry is illustrated by the judgment curve of Fig. 3a

In our earlier publications (1956, 1957) no explanation of this effect was offered It was examined over a wide range of conditions, how-

ever, with oot only white ooise masking in ooe ear but also various distortions (for example, severe amplitude clipping)

What distinguishes a "pure" signal from a ooisy or distorted ooe, thereby giving precedence to the former? Our first reaction was to assume that, in the case of speech, the listener's great experience of speech gives him prior information (and thus a set toward "pure" speech) But experiments sooo showed the effect to exist, equally strongly, with sources other than speech (such as combinations of sine waves of different frequency, and many others), of which we humans have far less prior knowledge Finally, we can destroy all effects of prior knowledge by using, as the binaural source $S(t)$, another wide-band white noise source, indepeodeot of the added noise source $N(t)$.*

Figure 3b shows a typical curve, which is quite asymmetrical about $T_e = 0$ Notice, in this case, that the "noisy noise" $S(t) + N(t)$ has takeo precedence over the "pure noise" $S(t)$

Clearly, then, the infereoce process by which the brain (fusion mechanism) discriminates between the two signals does not necessarily require prior probabilities (though with speech or other common signals such prior knowledge may conceivably enhance the effect) Receotly H B Voelcker (of our laboratory) has giveo a complete theoretical explanation of the effect, unfortunately, at the time of writing, this has oot appeared in print, so no refereoce can be given. Without anticipating its appearance, we might merely point out that the signal $S_R(t)$ is "contained within" the noisy or distorted signal $S_L(t) + N(t)$, but that the converse is not true Voelcker has examined the nature of the relation "contained within" mathematically, concluding that this precedence effect requires only a simple correlation analysis mechanism, which can be of the type that we have described as the basis of binaural fusion (Sayers and Cherry, 1957), and which is outlined in the section on The Model of the Binaural Fusion Process in the present paper In other words he observes that the processes adopted in our model are all that are strictly needed to explain the effect.

### Binaural Fusion of Speech

A great deal of auditory analysis is carried out with simple determinate signals, like clicks and pure sine waves Speech, which is the

* Perhaps we could give a psychological definition to white noise, as being "that signal of which the subject can have no prior microscopic knowledge (but only statistical knowledge), which prevents him from making predictions for a time ahead greater than the Nyquist Sampling Time."

class of signal of greatest importance in real life, has a very complex structure, but this does not preclude its use for such experiments as we are considering here. On the contrary, we regard as essential the use of speech and other stochastic signals, when attempting to build models of aural mechanisms—which, after all, have evolved around such natural sources.

The usual and most effective way of dealing with such complex "stochastic" sources as speech is to use statistical (average) methods and measures. The method we have adopted, for studying binaural fusion, is of the type illustrated by Figs. 1 and 3; our original paper (Sayers and Cherry, 1957) contains many more.

It is from the parameters of such statistical data that the parameters of the binaural fusion mechanism may be inferred. But such parameters must not be expected necessarily to remain invariant as the type of signal is changed (or the noise of the environment or other conditions). This variation we have found to be the case, in certain ways. But it is not the fusion *mechanism* that seems to change, rather it is extremely flexible in the way it handles limitless variety of binaural signals—speech, with its transients, its quasi random breath noises, its quasi periodic formants as well as all the myriad of other sound sources that surround us in daily life. Rather it is the *data* that the fusion mechanism recognizes as being "in common" between the two ears that are found to vary according to circumstances; if one class of data is not available in the stimuli, the mechanism finds another.

This kind of flexibility is, of course, indicative also of correlation processes being used by the brain. Before examining for the exact processes, let us illustrate this flexibility in the case of speech.

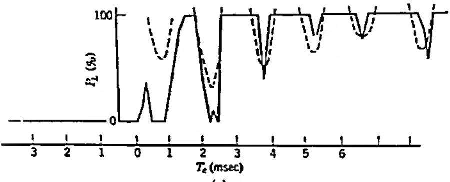
### *The data in speech controlling the binaural fusion process*

In this series of experiments, intoned vowels were used (to remove transients). They were recorded on tape, which was subsequently closed into a loop to provide a continuous source.

When such an intoned vowel is presented binaurally to a subject, the resulting "judgment curve" is exactly the same as that of Fig. 1*a* for a random or quasi random source (or replotted so as to eliminate arbitrariness of zero delay $T_s$ as in Fig. 1*c*). This is indicative of the fact that the random breath sounds, closely similar in both ears, control the fusion process; the formant periodicities are not apparent here.

But we can easily destroy the similarity of the breath sounds arriving at each ear by adding to one side a white noise generator, as in Fig. 2. What does the mechanism fuse on now? Figure 4*a* shows one example, with an average signal-to noise ratio of −9 decibels,

the difference now is that dips have appeared at values of $T_e$ that indicate that fusion is taking place on the periodic components (formants) of the intoned vowel source (which have known frequencies) Thus the fusion mechanism is operated by common breath sounds, under quiet conditions, but partly by the common formants when breath tones are rendered useless.



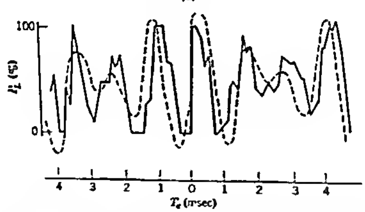




Fig. 4. Judgment curves for (a) the intoned vowel *a*, noise-masked in the left ear only, with signal-to-noise ratio −9 db (theoretical curve dashed), (b) two sinusoids (600 and 800 cps, equal level)

We shall not repeat details of the calculations here but merely state that the correspondence between the dips in the curve of Fig. 4*a* and the formant frequencies of the intoned vowel has been examined by Sayers (Sayers and Cherry, 1957), his calculated "judgment curve" is shown dashed on Fig. 4*a* Note the coincidence of the peaks Such a calculation, based on the mathematical model to be described in the next section, is possible with some accuracy because the formant frequencies and decrements can be measured accurately in this case of a steadily intoned vowel.

The asymmetry of the curve of Fig 4a representing our "precedence effect" should also be noted

## The Model of the Binaural Fusion Process

The few curves we have illustrated here (Figs 1, 3, 4) are typical of a very large number resulting from measurement with many different types of sound source and different listening subjects (Sayers and Cherry, 1957)

Let us look now at the steps involved in building up a theoretical model, by which such fusion "judgment curves" may be calculated for all sorts of sound sources—pure tones, chords, intoned vowels, noise, running speech.

### *The first "simple model" of binaural fusion*

The simplest interaural correlation process is illustrated by Fig 5 Briefly, we argue that the $L$ and $R$ signals, $S_L(t)$ and $S_R(t)$, are cross correlated and that the correlation function $R_{12}(t\ \tau)$ is represented upon a "conceptual surface," as shown by the dashed curve Then the "judgment mechanism" decides whether the function lies, on an average, more to the left or more to the right of the mid- ("intracranial") line The measure used does not appear to be critical, since only a dichotomous judgment is needed, for our calculations, we have used the normalized areas lying, left and right, under the curve $R_{12}(t, \tau)$ One additional operation is necessary at this stage, before cross correlation, the signals $S_L(t)$ and $S_R(t)$ need to be combined with their own mean values $A_L$ and $A_R$ (the method of combination used tentatively at this stage is simple linear addition) The reason for this is that these mean intensities can themselves also control the $R$ $L$ judgment and so must appear upon the "conceptual surface" This oversimplified operation is clarified in our final model, as described in a later section

Conventional cross-correlation is represented by the function

$$\Phi_{12}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{+T} f(t) \quad g(t+\tau)\,dt \tag{1}$$

but clearly this is not usable, since the aural processes are proceeding in real time, and integration over the future is unrealistic. Again, the brain cannot integrate indefinitely over the past, because judgments are made moment by moment, as sources of sound move about. Clearly, the process can only be one of short term *running correlation*,

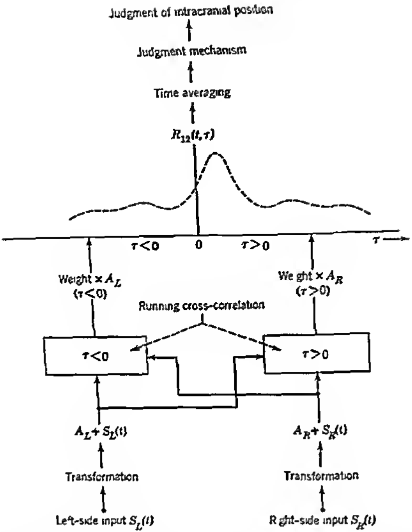



Fig. 5. Model of the simple cross-correlation theory of binaural fusion. Note that the running cross-correlation unit has been divided in two parts only for clarity of representation.

represented most generally by

$$R_{12}(t,\tau) = \int_{-\infty}^{+\infty} f(t-T)g(t-T-\tau)W(T)\,dT \qquad (2)$$

where $W(T)$ is a weighting function, corresponding to a short-term memory. The exact form of this function is not critical, we have found, but it is convenient to assume that it is exponential.

$$W(T) = \epsilon^{-KT}\Big|_{T>0} \qquad (3)$$

Licklider (1951) used a similar running correlation function in his model of pitch perception We have estimated the time constant $K$ here as approximately 6 msec This running cross correlation is illustrated by Fig 6

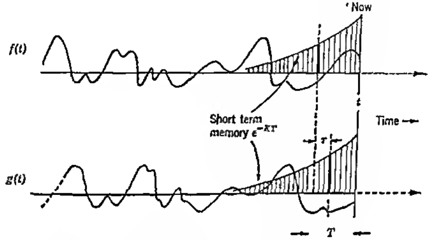



Fig 6 Short term running correlation, as from Eq 2.

### Theoretical results, based upon the "simple model"

The key to the exact form of the correlation process was first obtained from fusion measurements based upon single and multiple pure tones (see, for example, Figs 1b and 4b) Such curves appeared to be closely similar to the correlation functions of the signals themselves (for such steady state signals no short term memory $\epsilon^{-KT}$ was involved)

Notice one important thing about these curves, typical of all our measurements, they are "sawn-off" sharply at the 100-per-cent and 0 per-cent levels, corresponding to the listener's *absolute certainty* of $L$ or $R$ We shall cite only one example here Fig 4b shows (dashed) the calculated curve based upon the "simple model" when 600 and 800 cps are applied together binaurally This does not, of course, recognize the existence of these 100 per cent and 0 per-cent limits, since the model contains no "thresholds of absolute confidence"

### The complete model of binaural fusion

The "simple model" of Fig 5 was found to be inadequate for several reasons Predominant is the fact that the $L$-$R$ lateral movement of a fused sound image is controlled also by the relative *intensities* of the two ear signals $A_L$ and $A_R$, as well as by their timing in relation

to one another We have made many measurements of fusion "judgment curves," using, in particular, multiple sinusoids and intoned vowels, and have found the following a most surprising result.

Briefly, if the *form* of the signals $S_L(t)$ aod $S_R(t)$ is held constant, but their relative mean intensities $A_L/A_R$ are varied, the *form* of the

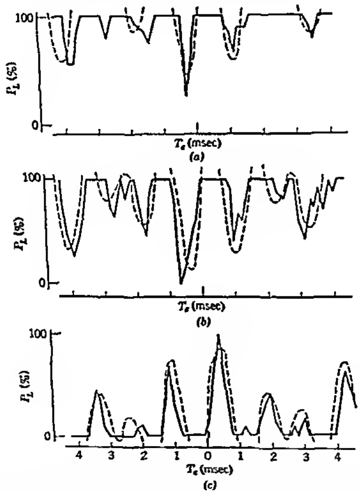



Fig 7. Judgment curves for two-sinusoid binaural signal, showing influence of interaural amplitude difference (600-cps component, −2 db with respect to 800-cps component in each channel) (*a*) $S_L(t)$ above $S_R(t)$ by 10 db, (*b*) by 6 db, and (*c*) by −6 db Theoretical curves dashed.

judgment curve itself also remains invariant, however, this judgment curve is moved bodily, up and down, between the "sawn-off" 100-per-cent and 0 per-cent limits Figure 7 shows one typical result, using two sinusoids, 600 and 800 cps, as in Fig. 4*b* also It is as though the 100- and 0-per-cent limits form a mask, behind which the judgment curve slides up and down, as controlled by the ratio $A_L/A_R$

Such a result is very simply accounted for if the relative signal amplitudes $A_L$ and $A_R$ at the left and right ears are assessed, by some averaging process, and used to weight the $L$ and $R$ sides of the correlation function $R_{12}(t, \tau)$ (see Fig 5) accordingly, before the final judgment process decides whether this function lies predominantly $L$ or $R$ of the mid- (intracranial) line

Such an assessment of $A_L$ and $A_R$ might well result from an additional *autocorrelation* process, operating on the signals at each ear separately Again, if this is short term, as for the cross-correlation $R_{12}(t, \tau)$ in Eq 2, running average values are assessed, $A_L(t)$ and $A_R(t)$, so that these are themselves functions of time Such a method of assessment provides, inherently, a theoretical basis for other binaural phenomena, to be referred to later

The complete model upon which calculations have been based is now shown in Fig 8 and is described in detail in our 1957 paper Briefly, the signals at each ear $S_L(t)$ and $S_R(t)$ are first subjected to separate running autocorrelation, and the two resulting functions are then cross-correlated

This cross correlation function $R_{12}(t\ \tau)$ is subsequently represented on a "conceptual surface" but, before the "judgment mechanism" decides whether this function lies predominantly $L$ or $R$ of the midline, the two parts of the function ($L$ and $R$) are weighted by a long term time average of the two autocorrelation functions, $R_{11_L}(t, \tau)$ and $R_{11_R}(t, \tau)$ There are, therefore, three "conceptual surfaces" involved, one at each ear and one in the center

Such a model is, of course not neurophysiological, but *functional*, it has been used for calculating $L$ $R$ lateral "judgment curves," with many forms of binaural signal, either identical at each ear or noise masked at one ear We cannot cite many here (other than Figs 3a, 4b, and 7) but would refer the interested reader to the original (Sayers and Cherry, 1957)

## Some Further Aural Effects Predicted by the Model

1 When the left or right ear only, but not both is stimulated, no centrally fused subjective image is formed In the model, only the $L$ or $R$ "conceptual surface," and not the central one is energized. Similarly, when the $L$ and $R$ signals are from statistically independent sources the same result obtains (Cherry, 1953)

2. When a complex source of sound applied binaurally has no frequency components below approximately 1200 to 1500 cps, it is an experimental fact that only the *envelopes* of the $L$ and $R$ signals fuse

into a binaural image, their microstructures do not operate the fusion mechanism (Leakey, Sayers, and Cherry, 1958). But when the signals

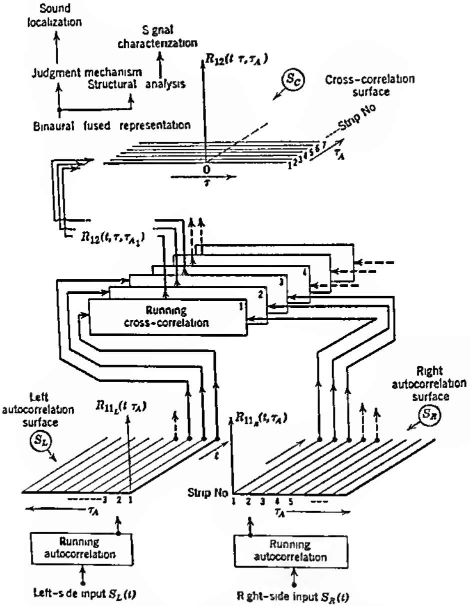



Fig. 8. Model including the proposed extensions to the basic theory, from which calculations have been made

are identical (or different) *pure* tones above about 1500 cps, with no varying envelopes, no fused image forms. This phenomenon assists our directional hearing of signals, all of whose components of wave

length are shorter than twice the distance between the ears Our fusion model does the same, since, under these conditions, the running autocorrelation processes at each ear automatically pass on only the envelopes (running averages) to the central cross correlation process

3 When listening binaurally to multiple sinusoids, the subject can, at will, listen to the whole fused chord, or to any one, or any group, of fused tones as distinct *Gestalten* Again, by independent time delay controls, each of these different fused images can, subjectively, have independent lateral movement Our model also enables us to calculate the "judgment curves" of lateral image positions for each of the images separately (Sayers and Cherry, 1957), since the preliminary autocorrelation processes perform the necessary periodicity discriminations

4 If, with binaural stimulation, one ear is, in addition, masked by noise, or if other perturbation is introduced, a kind of "precedence effect" arises which we noted in an earlier section Voelcker has shown that this can be explained only in terms of the short term auto- and cross correlation processes used in the model, but his work is not yet published

The relations between our model and the proposals made by Licklider (1956) concerning pitch perception might be noted here We have adopted the same running-correlation function as Licklider and, like him, we require both auto and cross correlation (although the order is reversed in our model) But our premises and experimental data are utterly different in kind Licklider is concerned with neurophysiological facts, we are not Again, it is on pitch perception that he concentrates, rather than upon the various fusion phenomena We have been concerned solely with building a functional model of fusion processes, that is, with a set of mathematical operations whereby we can *calculate numerically* the probability of binaural fusion—nothing else

It cannot be overstressed that models such as ours are to be regarded as "one of a class of models", it is always possible to take the mathematical processes cited and recast them, or transform them, into alternative processes Thus there is no *need* to restrict our processes to correlations, correlations can well be interpreted by filtering processes instead And, once again, it is not neurophysiology that concerns us here, but representations of behavior—entirely an "outside view" of the human black box.

A great many perception phenomena concern extraction of *statistical invariants* from among the raw sense data, for *Gestalten* are recog-

nized under many forms of transformation and perturbation—both determinate and statistical, for example, noise Again, the perceptions operate in real time, moment by moment.

Short term correlation thus seems to be a logical choice for the extraction of such invariants We end then with a somewhat vague suggestion that perhaps the various hierarchical processes of perception may be described by hierarchical successions of such correlations The question is whether short term correlations may not be the bricks of which part of the house of perception is built.

## Summary

In this paper a mathematical model is developed which is descriptive of the binaural fusion process Fusion of all types of signal can be handled sinusoids, noise sounds, intoned vowels, running speech, and so forth.

It is entirely stimulus response *behavior* that is described by the model, and no reference whatever is made to the physiology or anatomy of hearing. With the model calculations can be made, in complete detail, of the probability with which a human listener will hear sounds as lying to the *right* or *left* side of his intracranial plane, when binaural stimuli are presented with some mutual time delay The two signals (left-ear, right ear) need not be identical, fusion still occurs when they are different, as in fact they always are in real life Again, the mathematical model will assess the probability of fusion. Only if the two signals are totally unlike (statistically independent) are we assured of total failure of fusion.

The details of the model have already been published elsewhere In the present paper attention is paid particularly to the arguments underlying the development of the model Its relation to models of other hearing processes is clarified.

Finally, some typical examples are cited, comparing the experimental and the calculated results, and some general implications of the model for binaural perception are drawn.

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# 7

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# Peripheral Coding of Auditory Information

## Neurophysiological Specifications for the Form of the Auditory Code

The most strategic spot at which to examine and assess the information that enters the central nervous system through its sensory input systems is at the level of the primary afferent neuron In some systems, such as the cutaneous and the muscular, the afferent neurons are grouped into many separate afferent nerve bundles, but in others, notably the visual, olfactory, vestibular, and auditory systems, a single pair of cranial nerves carries the entire sensory input of that particular sense modality In the auditory nerve it is possible to record the action potentials of peripheral neurons that have not yet made synaptic connections It is particularly appropriate to use the auditory system as an example of neurological coding because information theory, which is obviously the background for our thinking about this problem, has developed primarily around auditory communication Perhaps the auditory system can serve as a model in this regard for some of the other sensory systems

The auditory nerve in man, and in mammals generally, is composed of myelinated nerve fibers of moderate and quite uniform size (3 to 5 microns in diameter) The cell bodies lie peripherally in the spiral ganglion inside the cochlea (Figs 1, 2) The cells are bipolar cells, and no synaptic connections in this ganglion are recognized (There is also a relatively small efferent bundle, the olivocochlear bundle or tracts of Rasmussen, with cell bodies in both the ipsilateral and the contralateral olivary complex We really do not know its function, and I shall disregard it deliberately ) In man the total number of afferent fibers, based on ganglion cell counts, is between 25,000 and 30,000 in each ear The number is about the same as the number of

sensory cells (hair cells), and the distribution of both ganglion cells and sensory cells along the length of the basilar membrane of the cochlea is approximately, although not absolutely, uniform (Davis, 1957, 1959, Stevens and Davis, 1938)

The relation of one set of sensory cells, the internal hair cells, to its nerve supply is fairly simple As a first approximation, we may think

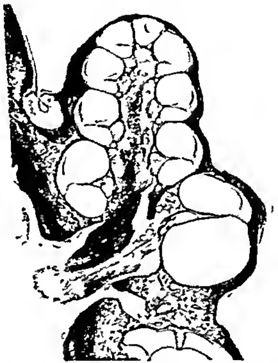

Fig. 1. Mid modiolar section of the cochlea of a guinea pig The cochlear canal is cut across nine times. The auditory nerve passes down the center of the modiolus and through the internal auditory meatus to the brain. The cell bodies lie in the spiral ganglion between the nerve proper and the organ of Corti on the cochlear partition. In this particular animal the nerve cells and the organ of Corti of the first turn had degenerated, following exposure to a high intensity tone of high frequency

of two or three internal hair cells as connecting to each fiber, and of each hair cell as receiving innervation from two or three nerve fibers (Fig. 3) A similar relation apparently holds for one class of fibers, the radial fibers, to the external hair cells, but each of the more numerous external spiral fibers innervates many cells, and each cell receives innervation from a number of fibers (Fernandez, 1951, Stevens and Davis, 1938)

In the overlapping innervation of hair cells, we find what may be

analogous to the peripheral nerve net of the cutaneous system and to the extrafoveal regions of the retina, where a considerable amount of overlap of innervation seems to be the rule The overlap may be simply part of nature's *margin of safety* or redundancy in the structure of the nervous system (I tell my students, "No single neuron,

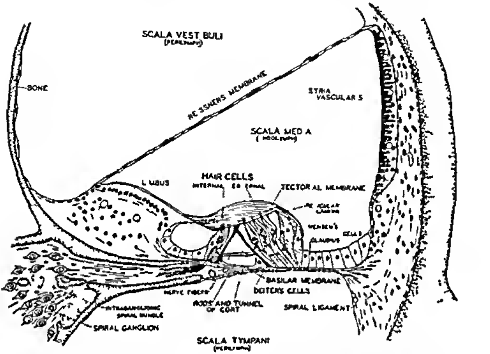


*Fig 2 Camera lucida drawing of a cross section of the cochlear partition in the* second turn of the cochlea of a guinea pig The bipolar nerve cells of the spiral *ganglion appear at the lower left. The nerve fibers have no myelin sheath in* the organ of Corti. The sensory cells are the internal and external hair cells.

unless it be an anterior horn cell, is ever completely indispensable") The overlap of innervation *also provides* at least the anatomical possibility of some interaction among sensory cells prior to the setting up of the familiar all or none impulses of medullated nerve fibers The peripheral endings of the sensory nerve fibers are nonmedullated throughout the organ of Corti They are completely naked, without even a Schwann cell sheath They should be regarded as a dendritic system. Conduction by electrotonus only or by decremental conduction is common in dendritic systems We have no right to assume that all-or none impulses followed by refractory periods arise until the auditory *fibers* acquire their myelin sheaths in the habenula perforata.

In the auditory nerve where it passes through the internal auditory

meatus, however, we find all or none impulses, separated in a given fiber by time intervals of at least 1 millisecond and usually somewhat longer (Tasaki, 1954) This form of conduction, typical of peripheral nerves and of white matter in the central nervous system, constitutes a very severe limitation for the coding of incoming sensory information

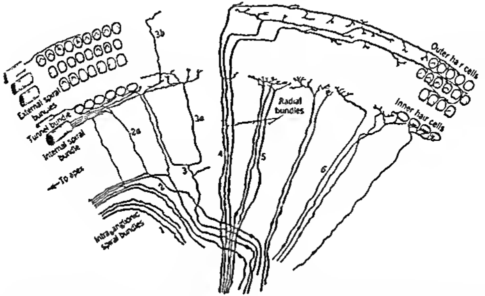


Fig 3 Plan of innervation of the hair cells, according to Lorente de Nó (in Wever, 1949) The intraganglionic spiral bundle is composed of efferent fibers. It arises in the medulla and does not have its cell bodies in the spiral ganglion

The dominant problem of auditory theory for many years has been to determine how the physical dimensions of the monaural acoustic stimulus, namely, frequency and intensity, are coded in the form of all or none impulses, separated by silent intervals and traveling in a large number of parallel, insulated channels A second problem, which has attracted more and more attention in recent years, has been the coding of the information that forms the basis of sensing the direction from which sound arrives Binaural differences in time become very important in this problem.

## The Classical Rules and Possible Mechanisms for Coding Auditory Information

From the work of Bekesy and many others, we know that the cochlea acts as a mechanical acoustical analyzer, and that the position

of maximum mechanical activity along the basilar membrane changes as a function of frequency (Békésy and Rosenblith, 1951, Davis, 1958*a*). It seems inescapable that an important part of the information concerning the frequency of the incoming sound waves, particularly those of high frequency, is carried by the built-in assignment of certain channels (nerve fibers) to certain parts of the basilar membrane. This arrangement takes advantage of the differential response to frequency of different sections of the cochlea. This is the *place principle* of coding of frequency (pitch) information.

It is also well established that for lower frequencies (below 2000 cycles per second or thereabouts) nerve impulses in the auditory nerve tend to group into volleys because each sound wave acts as a separate stimulus. Volleys of nerve impulses following one another at the frequency of the original sound waves have been observed in the pattern of nerve impulses as they pass up the auditory nerve (Békésy, 1959*b*, Békésy and Rosenblith, 1951). It has been abundantly proved in psychophysical experiments that information concerning the frequency of a low tone (its pitch) can be transmitted by nerve fibers other than those that are excited by a pure tone of that frequency. A high frequency noise that is periodically interrupted causes us to hear a low frequency pitch—its "periodicity pitch"—in addition to its high frequency spectral pitch. This is the so-called *frequency or volley principle* of auditory coding (Davis, Silverman, and McAuliffe, 1951, Licklider, 1951, Miller and Taylor, 1948).

In some sensory systems the *frequency* of discharge of impulses in each afferent fiber is an important method of coding information concerning the *intensity* of the stimulus. This form of coding seems to be of little significance in the auditory system. Experimentally it appears that the dynamic range over which the frequency of discharge in a given fiber is also a function of intensity is very limited, not more than 20 or 25 decibels (Galambos and Davis, 1943, Katsuki et al., 1958). Very likely the information concerning the intensity of an acoustic stimulus is more directly represented by the total number of fibers that are active than by the total number of nerve impulses in a given length of time.

A third method of conveying (coding) intensity information is by a systematically graded set of thresholds among the *receptor units* and a correspondingly graded contribution per fiber to the ultimate sense of loudness. In the ear there are two dimensions of systematic grading, both of them probably significant. First, the different rows of sensory cells probably have different thresholds and perhaps dif-

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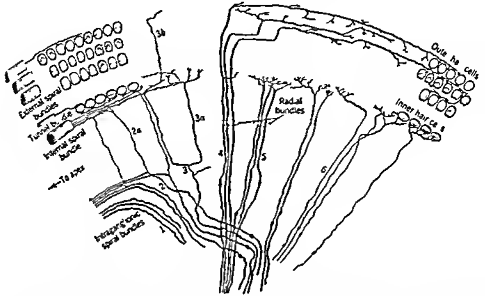


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ferent importance centrally Second, for a sound of a given frequency there is a point of maximum sensitivity somewhere along the basilar membrane Receptors that are located between this point of maximum sensitivity and the basal end of the organ of Corti can also be stimulated by this same tone, but its intensity must be increased Thus there is, for every audible frequency, a systematic grading of thresholds lengthwise along the organ of Corti

For the lateralization of the source of a sound, the two parameters of binaural difference in intensity and binaural difference in time of arrival of corresponding sound waves are both known to be significant. The importance of earlier arrival (the precedence effect), even by a small fraction of a millisecond, is well recognized The fixed anatomical separation of the two ears with the intervening acoustic baffle of the head gives a physical base on which nature has built into the nervous system a particular code, based on differences in time and differences in intensity appropriate to low and to high frequencies, respectively, to carry information relative to the direction of arrival of incoming sounds Considerable attention has been given to the "trading relation" between intensity and time There is a peripheral trading relation between intensity and time, because neural latency depends not only on the physical time of arrival of a sound but also on its intensity

It is not so well recognized that there must inevitably be certain small scale time differences (differences in latency) among the responses of the nerve fibers of an individual ear The traveling waves on the cochlear partition impose certain necessary differences in the time of arrival of the crests of the waves at different points along the cochlea (Fig. 4) This is true for acoustic transients as well as for sustained tones These time differences are a function of the frequency of the sound waves in question (Tasaki, Davis, and Legouix, 1952) If it is true (and I believe that it is a good general rule) that the central nervous system never fails to make some use of every bit of information that is presented to it, the consequent systematic differences in time of arrival of impulses in different nerve fibers are presumably utilized—although for what purpose we do not know Some other observations however, allow us to speculate concerning possible roles for these systematically delayed impulses and also for the synchronized volleys of impulses described earlier

We do know, as a matter of experimental observation, that individual elements in the midbrain and cortex are more "sharply tuned" than are the neurons of the auditory nerve (Katsuki, et al., 1958) It seems clear that inhibitory processes are at work and bring about the

## The Place of the Auditory System in Phylogenetic Development

Some insight into the coding and the nature of organization of each sensory system may be obtained from the generalizations formulated by G H Bishop (1959), elaborating the concepts of Judson Herrick, in relation to fiber size and to phylogenetic development Bishop points out that the central nervous system seems to have evolved by a process of successive accretion In the simplest, earliest vertebrates the primitive system was composed of relatively small nerve fibers that conduct rather slowly From the sensory point of view the system was sensitive, and from the organizational point of view it was well integrated Responses tended to involve large parts of the body in rather complicated patterns of movement for orientation, escape, food taking, and so forth The reticular formation of the central nervous system represents part of this primitive organization and so do some touch and pain fibers The cutaneous nerve net is probably a survival of this primitive form of organization

To the original primitive nervous system, which nevertheless still persists in the higher and more complicated forms, has been added a second and in some cases a third system These new systems supplement but do not displace the old The newer systems are characterized by larger, faster fibers and by discrete innervation The latter feature makes possible finer discrimination, better localization, and "mensuration" The absolute thresholds of the newer systems may not be so low, but the differential thresholds are smaller

The existence of two sets of receptors, fibers, and even centers for a given modality is in itself a form of coding, but we should not try to interpret this situation without looking at the organism as a whole I suspect that the key to this duality may be an ability on the part of the organism to accept or reject the information from one or the other of these systems as a whole, for example, by what we call "paying attention," or perhaps to use one set of information for one purpose and another set for another purpose or set of purposes

In the special case of the auditory system, the concept of old versus new does not turn out to be immediately or obviously helpful As nearly as we can tell, the cochlear system is a relatively late development in the evolutionary sequence It is certainly quite primitive in birds and reptiles and is fully developed only in the mammals The cochlear fibers are considerably smaller than the large fibers of some parts of the (muscular) proprioceptive system The labyrinthine

action potentials of the neck muscles, respiratory muscles, and so forth, of the animal, and (2) asynchrony of discharge of the volley of impulses The asynchrony is due partly to the Békésy traveling wave (Davis, 1958a) when the frequency is low, and partly to systematic variations in latency with the intensity of stimulation This is significant because some fibers in each volley are always near their threshold of response There are also spontaneous fluctuations in latency, and in the guinea pig, at least, there is systematically a greater length of fiber from the apical than from the basal region

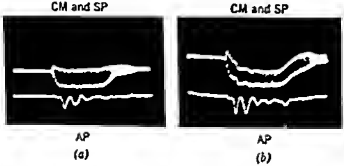


Fig 5 Cochlear microphonic (CM) and summating potential (SP) recorded by intracochlear electrodes from the basal turn of a guinea pig. The stimulus was a 7000-cycle tone burst with a 1 msec rise time The stimulus for the oscillogram in (a) was just maximal for CM for the oscillogram in (b) it was 10 db stronger Note that the CM is smaller in (b), whereas the SP (the d-c displacement of the upper trace) and the action potentials (downward "spikes" in the lower trace) are larger (From Davis, Deatherage, et al., 1958a.)

We have concentrated on two forms of stimulus that evoke well-synchronized volleys of action potentials from known regions of the cochlea (Fig. 5) The first is the onset of a tone burst at 7000 cps with a rise time of 1 millisecond. (We use 1 msec rise time in order to minimize the scattering of acoustic energy to other frequencies The frequency, 7000 cps, is selected as being high enough to give "summated" stimulation, without the volley effect, that is determined by the shape and amplitude of the envelope and quite independent of the individual sound waves, at the same time 7000 cps is low enough to allow us a wide dynamic range within the limits of our transducer; and finally it stimulates at a point on the cochlea that is anatomically accessible for the placement of electrodes ) The pattern of action potential response to such a stimulus is the familiar spike ($N_1$) fol lowed by successively smaller spikes ($N_2$ and $N_3$) at intervals of about 1 msec. This interval represents the refractory period of the auditory nerve fibers Incidentally, we should think of 7000 cps to